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No 51

EFFECTS OF CLIMATE AND MORPHOLOGY ON TEMPERATURE CONDITIONS OF LAKES

Aija-Riitta Elo

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Cover: (Photos by Aija-Riitta Elo)
Top left: clouds over Lake Vättern, Sweden.
Top right: night mist over Lake Neittamojärvi, southern Finland.
Bottom left: freezing pond in southern Finland.
Bottom right: cracking ice on Lake Neittamojärvi after the water level had fallen.

Aija-Riitta Elo

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Effects of climate and morphology on temperature conditions of lakes

Aija-Riitta Elo

ACADEMIC DISSERTATION IN GEOPHYSICS

To be presented, with the permission of the Faculty of Science of the University of Helsinki for public criticism in the Auditorium D101 of Physicum, Gustaf Hällströmin katu 2, 2 March 2007, at 12 o'clock noon.

Helsinki 2007

To Mika, to whom I wish all the best in the world; and to my mother, who is one of the people I wish had had easier life.

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Articles included in the thesis:

This thesis is based on the Appendix and the following original articles, referred to in the text by Roman numerals:

I Aija-Riitta Elo 1994. A Sensitivity Analysis of a Temperature Model of a Lake Examining Components of the Heat Balance. *Geophysica* 30, 1-2, 79-92.

II Aija-Riitta Elo, Timo Huttula, Anu Peltonen and Juhani Virta 1998. The effects of climate change on the temperature conditions of lakes. *Bor. Env. Res.* 3, 137-150.

III Aija-Riitta Elo and Steven Vavrus 2000. Ice modelling calculations, comparison of the PROBE and LIMNOS models. *Verh. Internat. Verein. Limnol.* 27, 2816-2819. http://www.schweizerbart.de

IV Esko Kuusisto and Aija-Riitta Elo 2000A. Lake and river ice variables as climate indicators in Northern Europe. *Verh. Internat. Verein. Limnol.* 27, 2761-2764. http://www.schweizerbart.de

V Aija-Riitta Elo. Energy balance and vertical thermal structure of two small boreal lakes during summer season. Accepted to be published in *Bor. Env. Res*.

VI Elo Aija-Riitta 2005. Modelling of Summer Stratification of Morphologically Different Lakes. *Nordic Hydrology* 36(3), 281-294.

VII Aija-Riitta Elo 2006. Long-term Modelling of Winter ice periods for Morphologically Different Lakes. *Nordic Hydrology* 37(2), 107-119.

Contribution of the author to the joint articles:

II:

The author wrote the introduction and the chapter describing previous studies related to climate change and is responsible for all aspects in the article concerning Lake Pääjärvi. The characteristics of the lakes examined in this article are compared with those of other lakes studied in prior research on the bases of measurements and similar model applications. She participated in taking measurements at the lake, collected the rest of the available data and designed its use in the model application. Based on the best information available, she designed the use of the transient scenarios in the model application. The transient simulations are based on the idea that the baseline represents natural conditions as much as possible and the applied scenario data represent estimated changes relative to the baseline. She is responsible for processing the measured and observed data and the scenario data, the model runs and the analysis of the results. The models of the other lakes in the article also use lake measurements and very similar model applications. The spatial approach takes different regions within the study area into account together with statistical scenario data and wind analysis. These results of these studies were combined in the discussion and summary with the results with the transient scenarios for Lake Pääjärvi. The author participated with others in planning, how the lake studies in the article were to be combined, combining and writing abstract and the sections about the PROBE lake model, the lakes studied, the discussion of the application scenarios, and the references. She was responsible for preparing the whole article for publication, including the editing of the technical material.

III:

The comparision of the models was planned by the authors. The presentation of the article was planned together with LIAG (the Lake Ice Analysis Group), led by John Magnuson. The author made the model application for Lake Mendota using PROBE model with data made available by Steven Vavrus. Vavrus made a model application for Lake Pääjärvi using the LIMNOS model and the data made available by the author. Vavrus provided the results of the application. The author collected the results of both applications, and compared them with each other and with the results previously obtained for the lakes with their model applications (Lake Mendota with LIMNOS and Lake Pääjärvi with PROBE). She wrote the manuscript and oversaw all aspects of its publication.

IV:

The author has treated the data according to the advice given by Esko Kuusisto and delivered it to the LIAG databank. She has also made the calculations and illustrations for the article and took part in writing and preparing the article for publication.

Correction

Article III contains an error on page 2816: The latitude of Lake Pääjärvi is 61°04′ (not 60°04′).

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Lake Aulangonjärvi. Photo by Aija-Riitta Elo.

Introduction

Climate change, especially in the context of the enhanced temperature rise – so-called "global warming" – become a topic for intensive scientific research around 1985. The winter of 1987 was particularly cold, and Eero Holopainen actively provided information about the related climate changes. SILMU, the Finnish Research Programme on Climate Change 1990-1995, was launched in 1990 and it become possible to study lakes in a project led by Juhani Virta. The main numerical lake model used by SILMU was the PROBE model. Attention was focused on Lake Pääjärvi, which is a relatively deep lake. This work was continued with a focus on the effects of morphological features of lakes. However, a great deal of effort was devoted to broad-based comparative studies of modelling. An essential aspect of the comparisions involved methodology and data analysis.

To a large extent, lakes can be described with a one-dimensional approach, as their main features can be characterized by the vertical temperature profile of the water. The development of the profiles during the year follows the seasonal climate changes. In Finland, where most of the research for this study was conducted, lakes become stratified during the summer. After overturn, water cools and an ice cover forms. Typically, water is inversely stratified under the ice, and another overturn occurs in spring after the ice has melted. There are only some exceptions to this basic behaviour. Conditions also depend on the location of the lake, and certain features have classically been used in studies to distinguish between lakes in different areas. These features have been used as bases for observation systems and even as climate indicators.

Although the basic behaviour is the same, there are many variations between lakes with different morphology. The aim in this research was to further understand and model these differences using the one-dimensional approach. The smaller the lake, the more important the effects of its boundaries. For these reasons, lake boundary characteristics have received special attention. The emphasis in this research was placed on lakes in Finland, especially in southern Finland, for comparisons of the use of standard synoptical meteorological data, downscaling and scales. One-dimensional modelling, concentrating on lake physical features, was the basic approach in this research.

The PROBE model includes an advanced turbulence model that can be used to obtain the vertical resolution. The effects of the boundaries of lakes are connected to their morphology, their shapes and forms. Those effects are found both inside the lakes, where the form of the lake effects heat exchange, and over the lake, where meteorological fields are strongly influenced by the surrounding landscape. The latter effects are closely related to the surface energy exchange and the treatment of input data.

The PROBE model was first applied to Lake Pääjärvi. Lake measurements were used, followed by synoptical data from a nearby station. The surface fluxes over this deep lake were studied with earlier measurement data and several parameterizations of the model. The available baseline data were expanded and transient-change climate scenarios in SILMU were used.

The solutions for the vertical temperature profile, the surface fluxes and the energy balance of the whole lake were further examined using micrometeorological data obtained from two small lakes during the summer season. They were also compared with the results obtained with a one-layer model, called the SLAB model, for lakes located in Sweden in rather similar conditions. Horizontal surface temperature variations were also studied using remote sensing.

The ice model of the PROBE application for Lake Pääjärvi was compared with the LIMNOS model applied in a study of Lake Mendota in Wisconsin (USA). That model included two layers for the water. Both of the models described both of the lakes successfully, even though they are located in different climates. Like Lake Pääjärvi, Lake Mendota is an ice-covered dimictic lake (stratifies twice during the year), but it is located in a continental climate zone. The PROBE model was also applied to Lake Constance, a large deep lake in Central Europe. Although the dynamics of that lake are complicated, it was possible to model it so that freezing, which occurs rarely, was described rather well.

The ice data were collected, corrected and analyzed to determine whether they were able to support lake modelling. Long meteorological data series were available from the city of Jyväskylä, which is located in the middle of southern Finland in the Finnish lake district, close to the lakes to be modelled. These data were also corrected and used to develop model applications, resembling a method whereby the data from one point are downscaled to describe the climate over more distant lakes. Lake data from morphologically different lakes were collected, model applications were made and long data series (about 40 years for summer seasons, and about 80 years for winter seasons) were used to clarify the effects of the morphological features of the lakes.

One of the lakes situated in a watershed, which was modelled also with an application for the hydrological model HBV. It was possible to calculate surface temperature and surface freezing and compare the results with observations and the results of the PROBE model application for the same lake. The importance of sheltering was further examined with an empirical model of the seasonal heating of the thermocline. The model was calibrated with a selection of very small lakes, the model was applied to the lakes selected for the long-term study and the results were compared. The relatively greater importance of sheltering was observed, but the results for the smaller lakes were rather similar.

1. Lake studies

Hydrology studies water in nature, often with an emphasis on its amounts and its circulation. Lakes are sometimes seen as reservoirs of water, but they have usually been studied on a much broader basis. Physical lake research began in Finland in 1892 with Oskar Nordqvist, who also studied the Baltic Sea (Simojoki 1978). Several famous lake studies have been closely related to limnology, e.g. classical works by Hutchinson (1957) and Wetzel (1975, 2001). These describe the early steps beginning in the late 18th century in Switzerland and Scotland. Hutchinson (1957) noted that the importance of lake morphology was recognized as early as in 1850 in a study of Austrian lakes. Limnology studies water as a substance and as a creator of an environment, but it has also been considered to be a part of hydrology. According to Järnefelt (1958), limnology was defined in 1922 to include all studies concerning inland waters, as well as some brackish water bays if they were not very salty. This is emphasized by using the term fresh waters. The quality of water and its composition have since become increasingly important, especially due to pollution problems, and they have been related to the ecological state of lakes. However, salt and other compositional factors in water often require different treatment due to their effects on density and other physical features. Studies of the Baltic Sea have usually been conducted by oceanographers. Hydrology and oceanography belong to geophysics, but limnological studies have generally been conducted by researchers dealing with inland areas. At the University of Helsinki they were included in the Faculty of Agriculture until 2004 and the founding of the Faculty of Biosciences. At the Helsinki Technical University, water-related research has been closely linked to agriculture and the construction of power supply systems, both of which are concerned with the construction of waterways in inland areas. Special technical attention has been paid to irrigation and flood protection.

Biological and chemical processes in lake water develop quite differently depending on the circumstances. Human activities affect the composition of water in many ways and unfortunately these effects are often harmful. They can change the ecological conditions, thus increasing or decreasing some natural or artificial compounds, and some changes can even be toxic. Often such effects are local, but they can be strong and rapid. Improved computational possibilities have made it easier to calculate currents and influent transport. In early lake studies, computational possibilities were much more limited and the study of transport was often considered to be of minor importance; in those days the harmful effects were generally smaller. Huttula (1994) used multidimensional models to study the transport of substances. He also used the PROBE lake model as the basis for modelling lakewater quality. In his model, temperature is calibrated first and then chemical and biological components are calculated. High salinity requires changes in the description of density in the model equations (Haapalainen and Leppäranta 1996, Omstedt and Axell 1998). Limnologist have also studied salty inland waters (Wetzel 2001), giving the composition of lake water a broader meaning. Salty lakes are abundant in certain areas, although they have often been regarded to be of less importance despite their local effect on evaporation. However, the lakes in this study have been treated as normal freshwater lakes.

The fact that lakes store water plays an important role in defining what a lake is: it is large enough and water stays there long enough. The shape of the surface and the form of the basin below the surface of a lake are typically closely related to the processes that formed them. Those processes are typically studied in geology, and in the USA and elsewhere many studies of lake thermics have been conducted by institutes of geology. The processes that form a landscape occur typically over rather long time scales, although some processes can be strong and rapid, as, for example, those associated with earthquakes. Slower land uplift can have also strong effect on lakes, the direction of rivers can change rapidly and shapes of watersheds can change entirely. As the lakes modelled in this study did not experience any changes in their morphology during their modelled periods, those processes did not need to be taken explicitly into account in the model applications.

2.1. Observations and measurements

Simojoki (1987) described the early phases of geophysics in Finland. The measurements of vertical water temperature structure and ice were among the first to be defined on a geophysical basis. In the beginning only some measurements were made, and typically that included much experimentation and defining what kind of studies would be best. Both the theories and the equipment used were under development. According to Simojoki (1978) the best-known geophysical studymade in Finland was done by Theodor Homén in 1897, as his professorial thesis. Homén considered the heat balance of the earth using the previously unknown term “turbulent sensible energy”, but he did not actually include advection in his atmospheric balance. He continued his studies and attached importance to the effects of radiation and heat stored in lakes. He also started to consider the basic hydrological elements in relation to each other: run-off, precipitation and evaporation. The first scientist to make temperature soundings was Oskar Nordqvist, starting in 1883 at Lake Kallavesi, later at Lake Ladoga, the Baltic Sea and elsewhere. Nordqvist's founding of the Evo Game Research Station has been regarded as a milestone in the history of limnology in Finland. Axel Heinrichs published snow and ice observations in 1890-1901, taking inland waters also into account. Homén started to study lake temperature and heat balance in 1892 as a part of his research on the interaction of earth's surface with the atmosphere. He served as the opponent at the defence of a doctoral dissertation submitted by Rolf Witting, who was the first director of the Marine Research Institute, founded in 1918. At first, Witting considered himself a hydrologist, later expressed the wish that studies of the Baltic Sea be separated from those of inland waters.

Simojoki (1978) also noted that the record flood in Finland in 1899 led Homén to include floods in hydrological studies. Since then, floods have been an important part of hydrology, especially in the engineering branch. The flood of 1899 had major practical consequences. It led to the founding of the Hydrographical Bureau in 1908, whose responsibility it was to collect information related to traffic, agriculture, hydroelectric power and other matters of scientific interest. Many lake observations have been included in its observation programmes, but the main interest has been in water levels and river discharge. For many years the Hydrological Year Books included a lot of information about ice, snow and water temperature. These observations have provided this study with very important data.

Lake observations have also been collected by the Central Meteorological Institute of Finland (Valtion Meteorologinen Keskuslaitos). Its ice cover records have also yielded valuable information. In the last decade of the 20th century financial pressure led to the reorganization of governmental activities and the Hydrological Bureau (until 1960 the Hydrographical Bureau). From 1970 to 1995 it was located in the National Board of Waters (Vesihallitus), Finland and the National Board of Waters and the Environment, Finland (Vesi- ja Ympäristöhallitus). In 1995 it was incorporated into the newly created Finnish Environment Institute (Suomen Ympäristökeskus (SYKE)), which is responsible for conducting environmental research.

The development of computational methods has been used to support a sharp reduction in observational practices. Improvements in measurement and recording techniques have made it possible to collect data that were previously unavailable. The Hydrological Yearbook for 1992 was the last to include traditional water temperature observations, taken that year from Lake Kallavesi and Lake Inarinjärvi. Lake Kallavesi was studied already by Simojoki, during his tenure at the Hydrological Office. In 1967 Simojoki become the first Professor at the Department of Geophysics in the University of Helsinki (later merged into the newly created Department of Physical Sciences). His studies have provided a lot of information and inspiration for this study. Other lake measurements and observations made at the Department have also been major source of data here, especially data collected in research directed by Erkki Palosuo and Juhani Virta. The micrometeorological fields were examined in a large Nordic study campaign made it possible to calibrate and compare methods thoughtfully.

In this study all model applications were based on lake measurements. Even when synoptical data were used, the applications were based on comparisons with a model that was first calibrated with lake data. The model applications were studied to describe the whole energy balance of a lake, not only its temperature profile.

2.2. Physical features of the lakes

Lake currents are typically horizontal, and the formation of stratification is the main feature. Although horizontal differences in water temperature are small, vertical differences are much greater. These differences are strongly influenced by the heat supplied from the atmosphere and by the wind. Heating is related to the location of the lake and the trajectory of the sun. Lakes in the so-called temperate zone are stratified during summer (from May-June to August-November), especially in the boreal zone. During the stratification period the vertical temperature profile can be approximated with two isothermal layers: the epilimnion and the hypolimnion. Between them the temperature changes rapidly in the so-called metalimnion.

The depth where the temperature change is largest is usually called the thermocline depth. Stratification occurs with heating at the beginning of summer. This basic behaviour is very regular, being rather typical for each lake in a given area. For some lakes climatic conditions in some years can cause overturn in the middle of summer. The shape of the lake can increase its vulnerability to overturn. Flow conditions, especially throughflow can reduce the stability of stratification. However, stratification has also been observed in rivers.

Wind piles up water and increases its potential energy, causing mechanical motion. The heat budget of a lake has been interpreted as the amount of heat that enters it between the lowest and highest heat content. Hutchinson (1957) described the history of the development of that formulation, mentioning studies done by Forel and Birge around 1900, among others. He also gives values for heat budgets for several lakes around the world. Forel (1901) used the maximum density temperature of 4°C to divide lakes into different types. It soon became evident that more typologies were needed. Wetzel (2001) describes seven main types on the basis of stratification and ice cover. During summer stratification the epilimnion becomes thicker and the thermocline sinks. This increase of energy has been related to wind and the potential energy stored in the water, using the concept "Birgean wind work" (Hutchinson 1957). This concept has been thought to provide an approximate thermal history during the summer. Stratification can also be defined using stability, which describes the work required for the wind to mix the water. It can be calculated with actual densities over the vertical. When stability is defined empirically from observed temperature profiles, different values are obtained for different lakes on account of a variety of horizontal effects and morphological factors.

The other important factor in describing the main thermal development is the winter ice cover. Periods with ice cover are longer and the ice cover is thicker the closer the lakes are to the polar areas. In addition, altitude reduces temperature, and mountain lakes can act like those relatively further north. Mountains can also shade and reduce global radiation, which can be very important particularly for small lakes. Shading can also reduce winds. Due to more intense heating, stronger stratification is found closer to the equator, where lakes are typically polymictic and overturn can occur in short intervals due to convection and winds. Further from the equator warm monomictic lakes are found. They have a long stratification period, but ice does not form and the cooler period is practically isothermal. Lakes have a permanent ice cover (amictic lakes) in the Southern Hemisphere. Cold monomictic lakes have short ice-free periods during which they are mixed at or above the maximum density temperature. Even at a greater distance from the poles lakes are typically covered by ice during winter. Because these lakes often have two turnovers per year, they are called dimictic. During winter, inverse stratification can be found under the ice. If the climate is warm enough ice is not formed and winds can mix the water during cooler periods. With sufficient warming such lakes have a clear stratified period. Closer to the equator heating is so intense that the lakes can remain stratified (warm monomictic). These three are the main lake types, but additional types have also been presented.

Ice forms on Finnish lakes each winter. In the present climate, when stratified water is cooled, overturn occurs, and typically ice forms as the water cools further. In autumn after overturn, a lot of heat is still stored, but the maximum isothermal temperature is approximately 13°C. Water cools, being rather isothermal along the vertical. Under ice inverse stratification takes place and the water close to the ice is very cold. Water in fresh water lakes reaches its maximum density at about 4°C. During winter some heat is typically also released from the bottom, but the fluxes are usually only 1-2W/m^2. Temperature under the ice can be close to zero for several meters in riverine conditions, but inverse stratification takes place in calm conditions.

2.3. Effect of climate and its variations on lake conditions

Energy transferred into lakes is basically generated by solar radiation, with other sources, for example lunar influence, playing only a minor role. Energy is absorbed by the water as well as by the surrounding land areas, amounting to about 45% of the short wave energy entering the atmosphere. The atmosphere admits most short wave radiation, but about 6% is reflected by the air, 18% by clouds and 6% by the earth's surface. Most of the energy, about 70%, escapes as long wave radiation, thermal radiation emitted depending on the temperature. The atmosphere includes substances and gases that absorb large amounts of long wave radiation, thus increasing its temperature. This is the so-called greenhouse effect. Water and carbon dioxide are the most important greenhouse gases in the atmosphere. However, other substances have higly important effects, especially when enhanced greenhouse effect is considered.

In calculations of the energy balance, all the components, including the transversal energy exchange, have to be determined. The energy balance applies to each sub-area, and changes in the stored energy and temperature can be calculated according to changes in the sum of the components. This method can be applied in computations of the energy balance of a lake, and with the heat exchange and a lake model the temperature profile of the lake can be solved. Advection can occur between neighboring areas. Globally, transversal transport is created by uneven heating, which results from the fact that those areas of the earth that are more perpendicular to the rays arriving from the Sun receive relatively more heating.

Winds are created when energy and temperature differences are balanced. Water behaves similarly, and large ocean currents transport water according to temperature differences and rotational effects. Due to viscosity differences, such changes take place faster in the atmosphere than in water. Lakes are so small that their horizontal temperature differences uare sually of only minor importance. Oceans cover about 70% of the area of the globe, and owing to their large volume, they play a very important role in temperature distribution. On a large scale, as a first approximation, winds and currents in the atmosphere and oceans are small deviations in the rotational planetary motion. This motion can be described with vector mathematics. Air pressure and isobars of constant pressure are among the most important concepts for meteorologists. All these factors also have to be considered when a one-dimensional approach is used, for example in the treatment of data that are observed or computed using climate models. Local point data require continuity and balancing when they are to be used with a lake model application. For this reason a great deal of effort has been put into computing the total energy balances of lakes that have been studied as exhaustively as possible.

Globally, short wave radiation and air temperature vary from location to location. The fact that the tilting of the earths orbit is related to the yearly cycle causes slightly different conditions in both hemispheres. An additional effect is caused by the fact that the most of the land areas and lakes are in the Northern Hemisphere. The large supercontinent system of Europe-Asia-Africa forms a huge land area. Ocean currents also influence the global climate. The rotation of the Earth also affects typical paths along which weather systems typically move. Typically, weather systems in Finland arrive from the North Atlantic. Occasionally pressure systems can cause cold weather from the north to enter northern Scandinavia and Finland. Because these sorts of factors influence the local weather systems for each area, they have to be described by the data as accuratelly as possible. Important changes can be caused by climate-ocean interactions that, under certain conditions can periodically affect local climates in relatively large areas. A typical example is the so-called El Niño Southern Oscillation, the effects of which on lake ice data have been considered by Magnuson et al. (2000). Weather has a direct influence on lakes, and lake conditions can often be related to the prevailing weather types.

Information about long-term climate changes is collected and analyzed by the Intergovernmental Panel of Climate Change (IPCC), and it issued its third assesment report on the state of the art in 2001 (McCarthy et al. 2001). Turbulence in the climate system varies on different scales in space and time. In principle, fluctuations in turbulence affect how the terms of the energy balance, especially advection, should be described on relatively short time scales. Variability of the climate is seen as changes in the weather. Meteorologists often use ten-year periods to define local climate features, but periods of 30 years are typical for analyses. Even 30-year periods may be too short for statistical analyses, especially of events that occur only occationally or just once a year. Trends are used to indicate development, but various problems result from using heterogeneous data. Researchers often look for some kind of average year, but since several meteorological variables are involved, combining and correction can be complicated. The prevailing weather types, formed by larger scale weather system developments, can differ from each other in many ways. The distributions describing variables can therefore actually differ from the usual Gaussian normal distributions, but the availability of suitable data can limit the use of distribution shapes. Sample standard deviations together with averages are usually the best means of describing them.

2.4. Morphology and its effects

Generally speaking, morphology is the study of forms and shapes. Morphological differences can be studied using a comparative method (Halbfaß 1923). With regard to lakes, the effects of morphology can be understood to mean the effects caused by shapes and forms of the lakes and their surroundings. These can be analyzed on the basis of a lake's geometrical dimensions. Surface area and depth are regarded as the most important morphological variables. Other important features are related to the shape and steepness of the lake basin. The landscape around the lake and its dimensions have effects, and their importance should be assesed in relation to time scales.

On a larger scale, land-water heterogeneity affects local climate conditions. This heterogeneity is particularly important in the. Typically, the boreal zone is characterized by large numbers of large and small lakes with complicated shore forms, and islands may interrupt the surface area. These factors increase variations in the roughness of the surface. When the roughness elements are high, friction is greater and more turbulence is generated. If the shapes are round and heights change smoothly, the meteorological fields are more laminar and smooth. High mountains shade, but smooth hills and valleys allow wind to pass relatively unimpeded.

The water surface of lakes is commonly smooth. Also the surrounding terrain in Finland is relativelly smooth; however forests and gentle hills close to lake provide shade. Winds are weaker along the shore and they can change direction suddenly, with both vertical and horizontal gusts. Further from the shores the wind conditions are more uniform, and on pelagial sites friction leads to the formation of an ideal logarithmic wind velocity profile. The heights of 2 or 4 m have often been used for measurements taken over lakes. The synoptic measurement height used by meteorologists is 10 m.

In summer, wind is an important cause of currents that form in lake basins. Currents and temperature differences in the water increase mixing and heat transfer. If mixing is strong, heat penetrates more deeply, and sheltering has less importance. If lake is large enough, rotational waves are also of more importance. Over long fetches waves can grow and reach greater heights. In deep, large, regularly shaped lakes seiches are also stronger and less disturbed. In principle, regular temperature patterns can be taken into account with some suitable method. Persistent features can be created especially by strong shading, basin topography or strong throughflows.

During winter, it is possible to observe the effects of lake morphology on ice and snow cover. Depth is the most important factor for freezing, because it is related to stored heat: large volumes delay freezing. Usually shores freeze first, but during break-up horizontal variations are typically more influenced by the atmosphere: the ice cover shields the water surface. During winter persistent winds can influence the depth of the snow cover over the lakes, and the amount of snow can affect ice melt. If the obstacles along the shores are not high, snow can drift over them smoothly, but steep boundaries increase snow accumulation. The lake bottom can release heat, which can intensify melting along the shore. Currents under ice can add local horizontal variations. It is also possible, especially in small lakes, that spring flooding can have some local effects even on ice cover. Heating can be accelerated once the snow has melted and heat absorbance increases over the darker land area. In Canada, Adams (1981) noticed that different types of ice and large amounts of snow caused differences in melting order between shores and pelagial areas.

2.5. Modelling

2.5.1. General features

The models used for lake studies are usually similar to those used in oceanographic and meteorological studies due to the fact that they require a description of the water surface. Lakes nevertheless have their special features that must be taken into account in lake applications. The most important of these features are the effects of the boundaries, the shores. Lake studies have often concentrated on related biological or thermometrical aspects, which has then permitted very specific calibration and solutions. On the other hand lakes are a part of the hydrological cycle: they store water. Hydrological variables, such as water level, are recorded from shore locations, and they seldom are representative of the whole lake. Unfortunately, hydrological data are therefore sometimes too limited to be used in lake models. Old data are often difficult to use, among other reasons because rivers have often been strongly manipulated.

For simplification's sake, lake models are almost always based on some basic shapes, typically basic geometrical shapes. In nature, however, the shapes of the lakes are usually complicated, which increases the need to study morphological factors. Lakes are often selected for study because they have already been studied for a long time and enough data have been collected. Comparisons between intensively studied lakes and their models can therefore give important information. Lake models typically need lake data, but the fact that meteorological data are seldom observed close to lakes has had important consequences for lake studies and model performance.

2.5.2. Overview of lake model development

Kari Lehtinen (1984) solved for effective diffusion using a constant maximal value *A* if stability *F* was smaller than critical stability F_c. Otherwise it was calculated with $AF_c^{-A2}F^{A2}$. Accordingly, his model was a so-called zero-equation model. One-equation models also use turbulent kinetic energy *k* to solve turbulent eddy viscosity $v_T = C'_\mu L_m \sqrt{k}$, ($C'_\mu$ calibration parameter) and mixing length L_m needs to be solved with some equation, e.g. for surface layer. Two-equation models also include an equation for dissipation of turbulent energy.

Goudsmit et al. (2002) discussed the use of turbulence models in enclosed basins. According to them, advective-diffusive models (such as SEEMOD, Minlake, CHEMSEE, LIMNMOD, PROTECH), which use rates for vertical transport, were suitable for bio- and geochemical studies in which chemical and biological processes have no considerable effect on transport. They stressed that the calibration parameters need to be well justified before they can be used in empirical models. They believe that turbulence closure schemes (such as the bulk model by Kraus and Turner, DYRESM, and *kε*- models like used in PROBE, GOTM) with equations consume more time, but they are suitable for studies of the effects of climate change and many related processes. They also conclude that such models are becoming more applicable as computational strenght improves.

Spigel and Imberger (1980) analyzed time scales of processes relevant to wind mixing, relative sizes, parameters describing wind strength, basin shape and stratification, mixed Richardson number, and the aspect ratio of the mixed layer thickness to length. The computer code of their DYRESM model described mixed-layer dynamics, shear production and mixed layer deepening without surface exchange (no cooling or warming), stratification and basin shape according to the subsequently discredited form:

$$\frac{1}{2}\left[C_T q^2 + (\Delta\rho/\rho_0)gh\right]\Delta h = (C_K/2)q^3\Delta t + (C_S/2)U^2\Delta h - \Delta_L \Delta t, \qquad (1)$$

in which $q^3 = u_f^3 + \eta^3 u_*^3$ was a definition, (u_*^3 is proportional to wind energy). C_K, η, C_T and C_S were model parameters to be calibrated. $\Delta\rho$ was the density difference between the mixed layer and the layer below with a thickness of Δh. The terms from left to right described the rate of change of TKE (little importance for lakes), buoyancy, stirring, shear production and losses of TKE from the mixed layer by generated internal waves. With weak winds, shear is not important, and energy from wind can be approximated with $W = \tau u_* \propto \rho_0 u_*^3$. The resulting shape, $(C_T q^2 + \alpha\Delta T g h)\Delta h/\Delta t = C_K^f u_f^3 + C_K^* u_*^3$, $q^3 = u_f^3 + u_*^3$ was the same as that used in the model by Kraus and Turner (1967). Their model, which was also used by Tyrväinen (1978), was a one-dimensional model of deepening of the thermocline using turbulent kinetic energy (instead of total kinetic energy). The water compartment of the LIMNOS model in Article III used a Kraus-Turner type model (Vavrus et al. 1996).

In the model application by Tyrväinen (1978) the equations for heat and mechanical energy were approximately connected to the two-layer model: $G=(\rho_a/\rho_W)^{3/2}(C_D^{3/2}\overline{u^3}/(g\alpha))$, where *G* is kinetic energy from wind, ρ_a was air density, ρ_w water density, C_D a drag coefficient, $\bar{u}$ was mean wind velocity and α was coefficient of expansion. Tyrväinen (1978) gave $\Lambda\frac{dh}{dt} = \frac{1}{(T_s - T_+)h}\left[2\left(G + \frac{Q_s}{\beta}\right) - Q_n h\right]$ for mixed layer depth and $\frac{dT_s}{dt} = \frac{2}{h^2}\left[Q_n h - \left(G + \frac{Q_s}{\beta}\right)\right]$ for temperature. Surface temperature was T_s and the temperature at the upper part of the hypolimnion was T_+. The lowest part of the epilimnion was at depth *h*. Net heat balance was Q_n, total incoming radiation was Q_s and β was the extinction coefficient. Λ was the Heaviside unit function, obtaining value 1 when $\Lambda = \Lambda(dh/dt)$ is 1, otherwise 0 (rising thermocline). The model by Tyrväinen (1978) used daily input: total incoming radiation, air temperature, relative humidity, cloudiness and wind velocity.

2.5.3. Numerical modelling of balances

The amounts of energy and water remain unchanged also when lakes are concerned, and the energy balance is fixed. Continuity is also maintained. The energy balance for the lakes can be obtained by summing the main components

$$R + LE + H + Q = \delta, \tag{2}$$

where *R* is the net radiation (short and long wave components), *LE* is the flux of latent heat, *H* is the flux of sensible heat, and *Q* can be approximated as the rate of change of the heat storage. *δ* is a residual, if any energy is missing, for complete balance it is zero. The terms of Eq. (2) are considered at the water-air interface, the fluxes are determined as positive when directed upwards, and heat storage inside the lake is positive if it is increasing. No other terms are included, but it is possible that heat is advected in some cases.

In its simplest form the lake can be assumed to be a volume of isothermal water. The temperature changes of a box-shaped volume can be calculated, but no information about the temperature distribution can be obtained without more information, including at least the depth of the thermocline and the temperature of upper and lower layer. For smaller lakes a simple approach is naturally better, but the deeper the lake, the more important its thermal inertia.

2.5.4. Lake water temperature

For the SLAB model, a box-shaped model having uniform temperature, Ljunmemyr et al. (1996) found that the mean depth of the lake can be used to represent the thickness of the surface layer or the depth of the box representing the lake. They gave Eq. (2) in the form:

$$\frac{\partial T_w}{\partial t} = -\frac{1}{\rho c_p D}(LE + H + R), \tag{3}$$

where T_w is the temperature of the water in the box, the derivative is taken with respect to time, *ρ* is the density of water, c_p is the specific heat of liquid water and *D* is the depth of the described lake box. This box was compared with the PROBE model with the *kε*-model for turbulence using same input. Micrometeorological data were used with fine-scale surface flux parameterization in Article V.

Lakes are often simplified in watershed models. The surface water temperature of one of the lakes was also compared with the distributed hydrological model HBV (Lindsröm et al. 1997) in a version that include a subroutine for lake water temperature calculation (Appendix, 7.5. Lake Jääsjärvi). The HBV model is a conceptual hydrological model in which each part is presented with separate submodels, between which water is transferred via precipitation, snow, soil moisture, subsurface and ground water models. Typical input includes precipitation, air temperature and evaporation. Precipitation basically tells how much water enters the watershed and the watershed, is determined as the area from which precipitated water is collected as outflow. Air temperature is a basic indicator of the processes that are taking place, for example whether water is being stored as snow or is evaporating from the area. A lot of information about the area is needed in order to describe it. The whole area is usually divided into sub-areas that act in similar way, but information about the water exchange between sub-areas is essential. Water flows from the headwater through the watershed to the ocean. The output is discharge and water level. The density needed for data on precipitation and air temperature is influenced by the details included in each watershed model. This is determined largely by the available calibration data and other details. Evaporation, surrounding land and its moisture are essential parameters. Lakes have been described in the HBV model structure as a part of groundwater storage, and evaporation from them has been estimated. The model used in Finland treats many lakes as basins whose volume and water level can vary. The need for separate treatment of lakes was recognized early, and in Finland lake evaporation has been the basis of determining evaporation in HBV-based watershed models. Lakes affect the timing of maximum evaporation. For lakes it is later than for land areas, particularly due to thermal lag. Typically, monthly values have been used. This lag has been included in HBV model for calculating the surface temperature with a time constant 1/*k* of one month (Lindström et al. 1994). The lag could, in principle, depend on the depth of the lake. The same approach was used with a one-day time step. Successive calculation of water surface temperature T_S is given as

$$T_s(t) = (1-k)\cdot T_s(t-1) + k\cdot T_A(t), \tag{4}$$

where t is the time step and T_a is air temperature. The surface is heated or cooled with a small time lag following changes of air temperature. This is suitable when thermal storage is not large and its influence does not last longer than the time step. As result, this method is better suited to shallow lakes. In summer direct heating via global radiation is very intense. If the effect of global radiation is not included, surface temperature does not rise enough. A correction was introduced:

$$T_s(t) = (1-k)\cdot T_s(t-1) + k\cdot (T_a(t) + r(t)\cdot l), \tag{5}$$

where the time-dependent variable $0 \le r \le 1$ represents the intensity of global radiation and l describes its influence on warming. The latter also includes the heating effect via global radiation in each time step in addition to the air temperature and the heat stored during the previous time step.

2.5.5. The PROBE model

The PROBE lake model uses the PROBE program, which solves equations for vertically one-dimensional, transient boundary layers. It solves vertical second-order differential equations of the form:

$$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial z}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial z}\right) + S_\Phi, \tag{6}$$

where Φ is a dependent variable, t is time, z is the vertical co-ordinate, Γ_Φ the exchange coefficient, and S_Φ the source or sink term.

The lake is described with an area-depth curve (also called the hypsographic curve) as a pile of boxes of height Δh, with the largest box on the top having the surface area. For each time step all the equations included for the formed model are solved over the vertical, with the equations for temperature and horizontal velocities being solved first. The temperature profile is obtained with the heat conduction equation written as:

$$\frac{\partial}{\partial t}(\rho c_p T) = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho \sigma_{eff}} \frac{\partial}{\partial z}(\rho c_p T)\right) + S_l, \tag{7}$$

where the source term S_l describes heat absorption in the layer. μ_T is the dynamical turbulent eddy viscosity (units Nsm^{-2}), kinematic viscosity is $v_T=\mu_T/\rho$ and effective value $\mu_{eff}/\sigma_{eff} = \mu/\sigma + \mu_T/\sigma_T$ is the sum of laminar and turbulent parts. σ_{eff} is the corresponding Schmidt number (Prandtl number for kinematic, Schmidt number for thermal). Turbulent Prandtl/ Schmidt numbers σ_T are calculated as

$$\sigma_T = \frac{\Phi}{\Phi_T} \frac{1 + \Phi'_T \left(C'_T - \Phi_T\right) B}{1 + B\Phi\Phi_T}, \tag{8}$$

where constants Φ=0.2, Φ_T=0.3, Φ'_T=0.155 and C'_T=1.6. Buoyancy B is solved with

$$\mathrm{B} = \mathrm{g}\frac{\mathrm{k}^2}{\varepsilon^2}\left[2\alpha_1(T - T_0)\frac{\partial T}{\partial z} - B_s\right],\ B_s = \alpha_s\frac{\partial S}{\partial z} - \sum_{n=1}^{N}\alpha_{C_n}\frac{\partial C_n}{\partial z}, \tag{9}$$

where the coefficient α_l=7.18·10^{-6} is related to temperature and the term B_S with its coefficients includes the effects of salinity (S) and other concentrations (C_n, in the sum total of N equations) included. In the summation N refers to the number of concentration equations that can be included in the model to be solved with the equation solver. For horizontal velocities u and v the normal equations can be written as

$$\frac{\partial}{\partial t}(\rho u) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho}\frac{\partial u}{\partial z}\right) + f\rho v, \tag{10}$$

where p is pressure and f the Coriolis parameter. Kinetic turbulent energy k is computed with

$$\frac{\partial k}{\partial t} = \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho\sigma_k}\frac{\partial k}{\partial z}\right) + \frac{\mu_T}{\rho}\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right) + \frac{\mu_T}{\rho}\left(-\frac{g2\alpha_1(T - T_0)}{\sigma_T}\frac{\partial T}{\partial z}\right) - \varepsilon, \tag{11}$$

where g is acceleration by gravity, T_0=3.98ºC is the reference temperature (maximum density), σ_k=1.4 is the effective (constant) Prandtl number. The terms on the right side describe, from the left to the right, diffusive transport, production by shear, buoyancy and dissipation. Dissipation is calculated as

$$\begin{aligned}\frac{\partial \varepsilon}{\partial t} &= \frac{\partial}{\partial z}\left(\frac{\mu_{eff}}{\rho\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial z}\right) + C_{1\varepsilon}\frac{\mu_T}{\rho}\frac{\varepsilon}{k}\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right)\\ &+ C_{3\varepsilon}\frac{\mu_T}{\rho}\frac{\varepsilon}{k}\left(-\frac{g2\alpha_1(T - T_0)}{\sigma_T}\frac{\partial T}{\partial z}\right) - C_{2\varepsilon}\frac{\varepsilon^2}{k},\end{aligned} \tag{12}$$

where σ_ε=1.3 is the (constant) effective Prandtl number, $\sigma_{1\varepsilon}$=1.44, $\sigma_{2\varepsilon}$=1.92 and $\sigma_{3\varepsilon}$=0.8. The terms on the right side can be interpreted as in Eq. (9). From left to the right they are diffusive transport, production by shear, buoyancy and dissipation. The second-order closure is made with

$$\mu_T = C_\mu\rho\frac{k^2}{\varepsilon}, \tag{13}$$

where C_μ=0.09. For lakes, no salinity or concentration equations were used in the temperature model, but in Article II in the applications using a version of the PROBE model with the water quality model (other lakes than Lake Pääjärvi) equations were used for computing concentrations. When concentration equations are included they should also be included in the equation of state, and the model is first calibrated using water temperature. The equation of state can be approximated with:

$$\rho = \rho_0\left(1 - \alpha_1(T - T_0)^2 + \alpha_S S + \sum_{n=1}^{N}\alpha_{C_n}C_n\right). \tag{14}$$

For deep lakes, an additional term has occasionally been added to the eddy viscosity of Eq. (13) in order to describe smoothing of the thermocline due to its motion. The term, called deep-mixing -$\rho_{ref}A_s/N$, (A_s=2·10^{-7}) is calculated with the Brunt-Väisälä frequency

$N=\sqrt{-\frac{g\Delta\rho}{\rho\Delta z}}$. In lakes deeper than 100 m the effects on density are so important that their corresponding equations should be checked.

2.5.6. Air-water surface and wind

A classical article by Kaimal et al. (1972) described the basic characteristics of surface-layer turbulence. In the open sea, disturbances caused by the shores are inconsequential and the boundary layer can be fully developed (stable situation reached). A review by Smith et al. (1996) summarized work done over a period of more than 25 years, including important advances in measuring systems. A review article by Högström (1996) summarized research done by meteorologists. The value of the Karman constant is highly important. It describes the surface layer and its value has an important effect on the results. It has been widely used for a long time and its value has been set at 0.4.

Many of the studies of the interaction between the water surface and the atmosphere have been done by meteorologists and oceanographers, but geophysicists in other fields have also been interested in interactions over the water surface. An example from geodesy was given by Kakkuri and Kääriäinen (1977). Based on work done by Kukkamäki, they describe how the geodetic measurements over water, according to the optical properties of the air, depend on the vertical air temperature profile. The importance of wind for certain conditions was also noted, but variations in humidity were not found to be as important. These results have not been obtained by all, but they have been important when most accurate geodetic measurements have been made.

Applications of micrometeorology have been reported from areas where small-scale variations are of relevance, e.g. in plant physiology (Aurela 2005). The variations over two lakes were studied using an in-depth analysis of measured micrometeorological variables, and their importance for lake conditions were further studied in Article V. These data were considered for use as input for lake models, ensuring that the energy balance was solved. In the PROBE model applications, the effects of small size and boundaries on usability for accurate temperature calculation were given special consideration. One of the lakes stratifies, and sheltering there is essential (Lake Råksjö). The other lake is so shallow that it remains practically totally mixed (Lake Tämnaren).

The turbulent surface fluxes can be calculated according to the Monin-Obukov similarity theory, accounting for stability with parameterization as shown by Launiainen and Vihma (1990): the vertical fluxes of momentum (τ), sensible energy (H), and water vapor (E), are given with the equations:

$$\tau = \rho_a \overline{u'w'} \approx \rho_a K_M \frac{\partial u}{\partial z} = \rho_a C_{Dz} u_z^2, \tag{15}$$

$$H = \rho_a \overline{T'w'} \approx -\rho_a c_p K_H \frac{\partial \theta}{\partial z} = \rho_a c_p C_{Hz} (T_s - T_z) u_z, \text{ and} \tag{16}$$

$$E = \rho_a \overline{q'w'} \approx -\rho_a K_E \frac{\partial q}{\partial z} = \rho_a C_{Ez} (q_s - q_z) u_z, \tag{17}$$

where, over the water surface, T refers to air temperature, q its specific humidity, and u_z is the horizontal wind component. ρ_a is the density of air and c_p its specific heat capacity. In Eqs. (15)-(17) the first quantities with the superscripts describe the actual variations calculated as co-variances. The lines over the products denote averaging over a short time period. The fluxes can be approximated with the following forms using recordings at two heights: the water surface (subscript s in formulas) and at a height z (subscript z) are chosen here. The values for K and C with their subscripts are corresponding bulk exchange coefficients. The formulations allow arbitrary observing heights, and the values of the exchange coefficients C are solved for at each interval. The flux of latent heat, LE, which is part of the energy balance, can be calculated as the product of the flux of water vapor and the latent heat of evaporation. Evaporation has traditionally been given as depth in meters per area per day. Several classical methods for solving the fluxes were described in Article V. They can be thought of being variations of Eqs. (15)-(16). With micrometeorological fine data, the fluxes were solved with the iteration method described by Launiainen and Vihma (1990), which was also used for comparisons in Article I, and the coefficients were calculated for each time step according to the actual measured stabilization situation. This method is also independent of the measurement height. The basic version of the model uses more sparse synoptical data; it has been used in most of the applications. In it, the wind stress in Eq. (15) is calculated with $\rho_a C_{Dz}$=1.69·10^{-3}. Eqs. (16)-(17) are treated according to the formulation presented by Friehe and Schmitt (1976): $C_{Hz}=C_1+C_H$ is determined using stability, which is the product of wind speed and the temperature difference: when stability is less than zero, the situation is stable, C_1=0.0026 and C_H=0.00086. When the product is positive, but less than 25°Cm/s, the situation is unstable, C_1=0.002 and C_H=0.00097. Otherwise, the situation is very unstable and C_1=0.0 and C_H=0.00146. Parameter C_{Ez}=1.36C_H, moisture difference is given with water vapor pressures, and fluxes are given in units W/m^2. All values are at the reference height of 10 m. The surface temperature should be the so-called skin temperature, which has been used in most of the applications; however the temperature measured at a depth of 1 m has often been used. The methods have been compared in Article I, together with bulk form parameters defined with water balance method, for Lake Pääjärvi.

The horizontal variations can only be estimated as an average effect in the one-dimensional lake model. These estimates were used in Article V together with micrometeorological measurements along the lake. The results obtained were in general accord with those obtained by Venäläinen et al. (1998). A similar method was used in Article II in the applications for the small lakes; reducing factors were used for different directions based on calibration and on differences in the landscape in each direction. The reduction factor on wind can be determined as a calibration parameter of the model, but the found value of the calibration parameter can also include other effecting factors besides the reduced wind.

2.5.7. Radiation and absorption

Radiation balance is composed of short wave and long wave radiation, both incoming and reflected. In this study, the importance of the various terms was studied in order to determine how different data can be used for model applications. In lake studies, incoming global radiation is usually measured at the lake. Global radiation can also be calculated, usually with the latitude of the lake, in reference to the trajectory of sun. Some measurements are typically needed in order to determine the correct level. If global radiation is measured, it can be used to estimate the cloud cover fraction, which is also needed in order to calculate long wave radiation from the sky (with air temperature) if measurements are not available. In the model, long wave radiation from the water is calculated using the theory of a black body, with the calculated surface temperature. Data are often available from synoptical stations, but the use of observed cloudiness data can be complicated. It is known that cloudiness can change very quickly and that cloud types and their transparency can also vary considerably. It may be important to estimate differences between different observation locations, observers and their methods. Some corrections were made in global radiation to account for the latitude and local conditions.

Measurements of reflected short wave radiation can be used to estimate of surface albedo. Typical values are often used if such measurements are not available.

Absorption of light energy can be described by the exponential bulk form $(1-\eta_s)e^{-\beta z}$, where η_s is fraction of the short wave radiation absorbed at the surface, and β is the extinction coefficient. The bulk form can be used for each layer. According to the basic properties of the exponential function, several values $\beta_1,\ldots,\beta_n$ can be used instead of one value of β. These can be defined separately for different wavelengths and different absorbing constituents, e.g. pure water and phytoplankton.

2.5.8. Advection

Advection can be present in many situations, and it has often been thought to explain the residual left in Eq. (2). Horizontal advection can be averaged over longer periods. The lakes modelled in this study were selected so that advection could generally be ignored.

Advected water may have a different temperature than lake water, e.g. if it comes from an artificial source or from ground water. Typically, river water has about the same temperature as surface lake water, and incoming water settles to the depth best corresponding to its density. Temperature stratification is seldom affected. River flow affects the water balance and the total volume of the lake. If the shores are very shallow, changes in the water level might be important. Temperature observation sites at shore locations may be affected, but that is an observational problem. When rivers are compared to lakes some additional factors need to be considered. Above all, shading can reduce the heating of river water, and air temperature is relatively more important. These differences have been discussed by Mohseni and Stefan (1999), Mohseni et al. (1999) and Caissie at al (2001), among others. They are a direct function of the different dimensional ratios involved, for the rivers are typically narrower than lakes.

Heat can also be conducted through the bottom, but for the lakes in this study this aspect did not need to be considered: lake measurements and test model calculations of heating through bottom confirmed its minor importance in summer. There was no special reason to assume that it would be important in winter either.

Water exchange can occur in larger lakes with many deep basins: water can flow from one basin to another with the internal wave motions in the basin system. Here too, the dimensions of the sounds are important, together with those of the basins. An example of the processes involved is described by Virta el al. (1992A), who observed strong currents in the sounds of Lake Päijänne during the stratified period as well. The thermocline depth was about 10 m (temperature 13°C), but its inclination permitted the intrusion of hypolimnic water at higher layers in the neighboring basin. The surface areas of two of the basins and their 10 m depth contours were 17.5 km^2 and 6.8 km^2 for Tiirinselkä and 26.4 km^2 and 17.8 km^2 for Lehesselkä, with maximum depths of 41 m and 57 m, respectively. Strong currents were also observed to affect temperature locally near such locations, but the measuring sites used for studying such transport processes were not necessarily representative of larger basins.

Precipitation can also advect some heat, but that is usually of minor importance. The amount of water is usually not large and its temperature is often close to the air temperature. Storms can produce large temperature differences and strong winds. Particularly strong winds can have important effects, but usually they are of short duration and only exceptionally strong wind can break the stratification. Cooling is limited to the surface and the surface temperature is soon balanced with that of the atmosphere.

3. Material and methods

3.1. Introduction

Temperature stratification, vertical temperature profile, as well as duration and depth of ice cover, were defined as the main features to be modelled with the one-dimensional approach. As these factors are very typical of the lakes in a given area they can be used as indicators of the climatic conditions. However, as there are nevertheless differences between these lakes, we had to determine how these could be explained and modelled with one-dimensional modelling supported by direct observations. On the other hand, a one-dimensional approach is well-suited to describing lakes and their main features, but on the other hand their small size greately increases the importance of the boundary effects. As a result the existing data needed to be related to the modelling. Direct observations play an essential role in constructing the model applications, and enough lake data must be obtained. Applications had to be selected carefully so as to resolve the effects of the morphological differences. The aim was to improve lake studies by making one-dimensional lake models more broadly usable in studies. Modelling can also help to resolve morphological effects in ice data.

Small lakes in the Evo District close to Lake Pääjärvi have been studied by modelling the seasonal heating of the hypolimnion (Virta et al. 2001). The model was applied on the lakes used in Appendix to gain information about how the PROBE model results can be related to even smaller lakes.

We made a version of the distributed hydrological HBV model including a sub-model for lake water temperature calculation. That was done to compare the results obtained for one of the lakes with a PROBE application and observations.

3.2. Model use

Lake Pääjärvi is deep and its surface area is relatively small. The shape is rather regular with one deep basin. Floats have often been used in Finland to measure horizontal effects on evaporation (Järvinen 1978). A float was installed in Lake Pääjärvi in order to make measurements for a model application. The PROBE model was adjusted and its sensitivity was evaluated (Article I) using several surface flux estimates. These fluxes and the energy balance were further analyzed using fine-scale micrometeorological data from two small lakes. One of them was very small and stratified during the summer, and sheltering was essential. Although the other lake had a larger surface area, it was so shallow that it was almost totally mixed throughout the summer. Which surface flux routines should be used depends on the data: if micrometeorological data are available, more accurate routines can be used, but with coarser data the usual model routines give reasonable results. Synoptic data were adjusted for the model of Lake Pääjärvi (Virta et al. 1996) to obtain longer baseline data, and climate change scenarios were used (Article II). Synoptic data were modified to correspond to conditions over the lake. The application for Lake Pääjärvi used a deep-mixing routine that has been found suitable for use with deep lakes. More statistics were obtained with long-term meteorological data series from the city of Jyväskylä. These data were transferred to several lakes in the vicinity. It was not reasonable to make modifications on the data representing lake conditions, because micrometeorological conditions can vary from lake to lake. The aim was to make the transfer of data as systematic as possible, and the Jyväskylä data were compared with data obtained from stations around the area to account for the main differences in climatic conditions. With this data, the deep-mixing routine was no longer suitable, but it was possible to adjust the model without it. For Lake Valkea-Musta, a small lake, additional lake data were needed for adjusting, and measurements of the global radiation were used.

Precipitation data can be used to calculate ice cover, but this was not necessary in the application for Lake Pääjärvi. Comparisons of the ice models also used precipitation (Article III). These comparisions were made between Lake Pääjärvi and its application with the PROBE model and Lake Mendota with an application for the LIMNOS model. Some differences in ice dates were obtained if the PROBE model used a separate snow calculation: ice formed on the average one day earlier without the separate snow cover, and ice break-up was three days earlier (Elo 2002).

Lake Constance is located on the border between Germany, Switzerland and Austria. This lake has been included among the lakes studied in the EU's REFLECT and EUROLAKES projects. A PROBE application with the ice model was applied to it despite the fact that the lake is rather large and has complicated dynamics. However it was possible to model the rare freezing in the year 1963 and to obtain reasonable surface water temperatures with the data available. For this deep lake, the value used for the extinction coefficient showed relatively strong effects. The winter 1963 was also severe in Finland. A group in Switzerland studied the long-term development of Lake Zurich (also as a part of the REFLECT project) using a similar model with good results (Peeters et al. 2002). Their main interest was in deep water warming in winters over long time scales in connection with warming trends.

3.2.1. Special aspects of numerical modelling

In meteorology, a synoptical scale is determined as the density of observations in space and time needed for forecasting systems. These systems are limited not only by computational possibilities but also by the chaotic nature of the atmosphere. Therefore, despite accurate calculations, the reliability of the forecasts diminishes rather rapidly and their prediction power is usually substantially reduced already after ten days. The data interval in synoptical observation systems is typically three hours, which captures most of the diurnal variation. The spatial density can vary, but observations in southern Finland are made at several stations. On a macro (synoptical) scale, the time scale is over 48 h, with a corresponding length of more than 500 km. Synoptical cyclones, which typically travel over Finland and affect its weather, have a diameter on the order of 100 km horizontally. The micro scale is typically defined as being less than one hour and 20 km long. On this fine scale, turbulence is created when air flows around obstacles in the landscape and the height of these elements is comparable to the formed eddies. The meso scale is between the macro scale and the micro scale. The wind spectra have two peaks: 3-4 days corresponding to synoptic scale and 10-100 s for turbulence, but spectral intensity is low on the meso scale.

Articles I, II and III are based on synoptical data gathered at three-hour intervals, as well as on lake measurements. In Article II special treatments were considered in order to adjust the scenario data for changing climate. In Articles VI and VII the data were obtained at a meso scale distance from the lakes. At this distance weather systems are thought to travel over the area rather unchanged. Comparisons and corrections were made using data from the surrounding stations. Because the focus was correspondingly on seasonal features, local variations of the climate, if any, could not be observed. All the applications were adjusted with lake temperature measurements, but some additional lake data were used in some cases.

In Article V with fine data, the PROBE lake model was also tested using data taken at even shorter intervals, but it was soon evident that it hourly data was satisfactory. Changes over it cannot have a rapid effect due to the thermal inertia of the lake. It is important that the data include diurnal variations, especially in light. Hourly data describe these well, and often three-hour data are also sufficient. Some short-term meteorological phenomena can have a considerable impact, especially intensive storms, whose effect can be slightly underestimated with more sparse data. Usually strong winds continue over a longer period of time, and strong mixing quickly ensures that water temperature is affected by weather changes. Some storms were observed during the recorded measurements at the lakes Råksjö and Tämnaren, but they lasted for only a few hours and their importance remained minor (Heikinheimo et al. 1999). Daily output values are suitable for describing the seasonal vertical temperature structure and its development, but three-day output can shed light on observed features. It was important to check the numerical stability and accuracy of each application, taking into account the practical possibilities. Concerning the numerical calculations, density can affect the results and should be checked.

3.2.2. Freezing, ice growth and break-up

In the model, in principle, ice first grows to its maximum value and then begins to melt, however there can be several such episodes throughout the winter season, depending on weather conditions. In addition, the surface heat flux during winter is approximated to see whether it favours ice growth. If it does, the cumulative negative air temperature is used to determine ice thickness, and cumulative positive air temperature is used to calculate ice melt. The physical analytical bases for ice growth are explained by Leppäranta (1993) in a study involving brackish and salty seawater. Leppäranta stressed the importance of snow cover and its packing for sea ice. Special issues must be considered when lake ice applications are made above all, possible differences in determining constants and their time evolution. For lakes the vicinity of the shores affects the snow cover.

The model approximates heat balance during winter. The most important simplifications are that evaporation is ignored and given a zero value during ice cover. The temperature of the snow cover is also approximated, and air temperature is used when the temperature is below zero. When melting occurs, snow surface temperature is assumed to be zero, which has been found to be a good estimate (Cheng 2002). The surface balance estimate can also be used in deciding whether the ice cover has formed.

The main reason for ice growth is cold air. Cooling freezes water, and, due to density difference, the ice floats. For lakes, the conditions during freezing are typically calmer and the water composition is different from that of the oceans (Adams 1987). Lake freezing takes place relatively rapidly and the c-axes (the symmetry axis of the crystals) can be oriented horizontally, vertically, or both. Although horizontal growth is favoured in salt water, vertical crystals are often found in lake ice. The crystals grow vertically along the heat exchange between the water and the atmosphere.

In the model, the ice cover is formed when the temperature of water is cool enough. Usually the limit is 0°C, but for Lake Näsijärvi it had to be lowered to -2.5°C, otherwise the ice cover formed too early. Ice growth is described with the degree-day factor as

$$\eta = K_g \left[\Sigma(-T_a) \right]^{1/2}, \tag{18}$$

where η is the thickness of the ice in meters, K_g = 0.02/°C$^{1/2}$ describes snow covered ice, and $\Sigma(-T_a)$ is the sum of the average temperature of the air over the days when the temperature is below the freezing point.

The first model for Lake Pääjärvi in Article II did not include a separate snow cover, based on information about the permanent snow cover in that area (Solantie et al. 1996). Data from several lakes showed convincingly that the snow is practically melted when ice is 30 cm thick. This was used for the model applications for lakes in Finland in Article VII, and ice and snow cover were not treated separately.

Original formation of ice crystals, their growth and absorption of heat during thawing influence the final ice break-up. In ocean brine, pockets of salt water remain in the ice. In lakes, impurities also remain between crystals, and their concentration and form can affect melting. The daily decrease in ice thickness $\Delta\eta$ in meters is given as

$$\Delta\eta = K_m T_a, \tag{19}$$

where K_m=4.3.10^{-3} m°C^{-1}, and T_a is positive or zero. The combined effect of all the factors affecting climate is expressed as the degree-day factor K_m. This factor may naturally have different values in different surroundings and different times during winter. A study of its values in different areas in Finland has been made by Kuusisto (1980). The effect of various factors is often difficult to resolve, and while precipitation is certainly involved, but Kuusisto's work did not clarify the effect of radiation. Generally, he observed the following features: the values are larger in the south than in the north and in open than in forested areas, and the values grow larger as winter approaches spring. Kuusisto's findings were used to adjust the value of K_m relative to the value used in the model of Lake Pääjärvi, which was used in the calibration of radiation data, among other data.

Limits are used in the model for minimum thickness and wind velocity: when the ice cover is thick enough, it covers the water and alters both energy exchange with the atmosphere and flow conditions under the ice. Correspondingly, in the model, surface fluxes change, and turbulence equations are not longer solved; however convection can occur. Wind can break the ice when it is thin enough. Minimum ice thickness is 0.1 m, and ice breaks if the wind is over 6 m/s.

3.2.3. Underwater light conditions

The contents of water, e.g. salinity and bio-optical material, may have special effects on temperature, because they can also have vertical fine structure interacting with the temperature profile. The contents of the water of these lakes does not favor the formation of additional stratification, for example via salinity. Water density is calculated according to the water temperature, the formula used being best suited for water close to 20°C. More detailed description together with other, more detailed formulations could give better results for short term fine-scale calculations, for example calculations close to the maximum density at 4°C. Bio-optical material is typically mixed in the euphotic zone within hours, the mixed layer depth is considerably greater than the euphotic zone. Strong phytoplankton growth also requires time. Advection can typically transport substances from a river, but horizontal transport appears to be of minor importance in the lakes studied. Maxima of organic matter may be present at different depths due to adaptation to certain illumination levels or to certain temperatures. Significant deviations were not observed in the profiles of illumination at different depths in Lake Räksjö and Lake Tämnaren; the euphotic zone in both of these lakes was also thin compared to the euphotic zone in those lakes where such local vertical deviations have been observed.

In Article V the LiCor measurement spectra in water were divided into five bands, and a separate β value was calculated for each band. The fractions of the incoming short wave radiation, 400-800 nm, were also deduced from the data. The values for Lake Råksjö and Lake Tämnaren were based on actual measurements.

The extinction coefficients used in the articles (except Article V) were based on available secchi depth measurements. For Lake Pääjärvi, some LiCor measurements were also available. Secchi depth z_s stands in a simple relationship to the extinction coefficient β (this relationship is usually used in the basic version of the PROBE model) $z_s = 1.7/\beta$, and the value of 2 m is rather typical for the area. Some observations were used to estimate the heating of the hypolimnion in small lakes close to Lake Pääjärvi in the Evo District (Appendix 6.2). For this purpose, observed secchi depths were used with temperature records. Additional observations have been described by Eloranta (1978) and Jones and Arvola (1984). Other changes for example in land use, may also cause properties of water to change in a critical way. Typically, such changes take place over long time periods, during which the contents of water change slowly according to changes in inflows. The waters in Finland are typically dark, visibility is poor, and the changes are usually not great. Studies of the optical properties of inland waters from the beginning of the 20th century generally show that no substantial change were found from the lakes (Witting 1914).

Measurements of light conditions under the ice have often been made in connection with temperature profile studies. The temperature under the ice can be close to zero at a depth of several meters in river conditions. In calm conditions, convection balances temperature differences and a thermocline is formed. Leppäranta et al. (2003) noted a thermocline in the Estonian lakes during a mild winter at the depth of two to four meters, rising to about 1.5 m in March. Fresh water at maximum density at about 4°C tends to sink, and convection works continuously to lift water with a lower density; however some thermal diffusion can also occur.

3.3. Observations

3.3.1. Temperature

First, observation of water temperature profiles were collected by soundings with reversing thermometers, which were lowered and raised. Then, much more frequent data were obtained with temperature recording chains. It was possible to install chains for longer periods and, as they remained longer in the water, measurements were only seldom disturbed. At shore sites thermometers were not read until they were lifted out of the water. More recently, observations have been made with devices that have sensors that record water level automatically. Usually, surface temperature is also recorded. Measurements, including temperature soundings and recordings, have been collected by the Department of

Geophysics of the University of Helsinki, where studies have been directed by Erkki Palosuo and Juhani Virta. Data on meteorological variables over lakes have also been gathered in order to describe lake conditions. Measurements were also made in cooperation with the Finnish Meteorological Institute in order to obtain micrometeorological variations over lakes in more detail (Article V). Lake water temperatures were also recorded.

The long-term temperature measurements have been made in two types of sites: at a deep point in the lake basin, representing pelagial conditions, and close to the shore. The depth of 0.1 m has been used to represent the surface water temperature. For practical reasons, the measurements have been made in connection with other activities. Water samples have often been taken from the pelagial area, typically from the deepest location. The shore sites, often in sheltered bays, have typically been used for observing the water level. There are differences between shore and pelagial cond itions, and the time of day is also an important factor. The shore observations have been made in the morning at 8 o'clock. Pelagial measurements are made later during the day, when the water is usually warmer than in the morning. Pelagial sites are typically cooler due to larger water volume and more effective wind mixing, and the variations may be larger in shallow bays. Changes of the observation site or its conditions may also affect the observations and their representativeness.

Korhonen (2002) has described the water temperature measurements carried out by the Suomen Ympäristökeskus (SYKE). Long-term water temperature profile data and shore site water temperature data used in this study were obtained from SYKE and Pirkanmaan Ympäristökeskus (Pirkanmaa Regional Environment Centre).

3.3.2. Ice observations

The SYKE registers include ice data collected in Finland (Korhonen 2005). Most of the ice data used in this study for Finnish lakes were obtained from those registers. The available data were studied, corrected and selected for use depending on the modelling approach. An analysis of the Finnish data, as climate indicators in northern Europe was presented in Article IV. The Finnish data used here were also entered into the global LIAG database, which included most of the ice observations useed. The additional Swedish data are from Eklund (1998).

The ice cover observations usually include the dates ice formation and break-up were observed. Ice formation usually takes place in phases and freezing is defined as having taken place when the whole lake surface can be considered frozen. Break–up is defined to have occurred when the whole lake surface is free of ice. Phases of break-up have also been identified and observed, but not often. Simojoki (1940) analyzed the duration of the processes of freezing and break-up over the entire lake surfaces. Unfortunately data related to the phases of freezing and ice break-up were either not stored in SYKE, or were not available. As the PROBE lake model is one-dimensional, it is not be possible to relate this data directly to output, but the periods of partial ice cover can describe the range of time when the whole lake surface cools enough for freezing. Successive ice formation and break-up periods were often obtained several times in winter in warmer climate. That can indicate that partial ice cover periods may be more frequent in warmer conditions.

Special problems attend ice cover observations: they have often been made in conjunction with *observations of water level, and the sites have been selected for that purpose, not in order to represent ice formation*. An additional problem is that instrumented automatization has led to the end ice observations. Some attempts have been made to use camera systems, ranging from satellites to fixed cameras close to the lakes. The results are complicated, especially due to problems involved detecting ice coverage from the obtained pictures.

3.3.3. Ice and snow cover measurements

The measurements of ice and snow cover include measurements of thickness of total ice cover, solid ice (frozen water), snow cover and slush ice (also called snow-ice). In addition, the water level is measured, relative to the hole made in the ice, as this is an indication of the pressure on water. These measurements have been made according to methods described by Palosuo (1965) over several years, and the method is still being used.

Palosuo (1965) discussed slush ice, which is often very important for ice conditions in Finland. It is formed when water freezes over regular ice cover. Water can be melted or precipitated during mild seasons. Fallen snow can also change into ice, but that aging is typically such a slow process that it would take some years and continuous increased pressure for it to become ice. During the winter, the snow that has fallen on lake can increase the weight of the ice cover so much that water rises over it through cracks. This can be influenced by flows and changes in the water level (Simojoki 1966). Some of the resulting effects can be relatively strong. Temperature changes can cause ice to crack, especially in polar oceans where temperature differences are typically greater.

Normal solid ice is often very opaque, called black ice, it appears very dark because it reflects very ligth. Slush ice (or white ice) and, particularly, snow are grey and white, and only some light penetrates them. Impurities increase absorption of light and melting. Slush ice exists in certain climatic conditions, and it is typical of Finland. In southern Sweden the climate is so mild that the lakes do not freeze every year, and slush ice is more likely to be found in the North.

Duration and severity of the ice-covered period affect the ice cover. Adams (1981) has found that some lake processes compensate for each other. For example, in conditions of white ice and snow exist less black ice is formed. Ice thickness is a very complicated variable. Frost sums and snowfall totals can even be similar, but for different lakes and years, considerable differences can be observed in the maximum total ice thickness. Usually in Finland it is 70-90 cm, which is similar to what has been reported from Lake Baikal: the total ice, for the whole Lake Baikal corresponds about the same amount of ice that was found in Finland for all the lakes during the maximum thickness of ice cover, approximatelly 225 million metric tons in the period 1961-90 (Kuusisto and Elo 2000B). Typically, at least in Finland, snow melts first and after that ice begins to melt.

Measurements of horizontal snow distribution on lakes have been made by Simojoki (1940), Kuusisto (1973) and Eklund (1998). They have found approximately the same depth of snow over most of each lake. There can be large variations of snow cover horizontally over the lake surface, but in principle these variations are reduced over open areas. The shape of the lake and its surroundings can, in principle, influence the horizontal depth distribution of snow on the lake because they influence the wind.

3.3.4. Global ice data

As ice cover is directly related to cold temperatures it has been used as an indicator for climate. Some series of ice data are even longer than meteorological series, and ice data are used to describe climatic conditions all over the globe. Typically lakes in southern Finland freeze well before the end of the year and only in very mild winters has freezing occurred at the beginning of the year. In different climatic zones freezing occurs at different times. For many decades, Lake Mendota in Wisconsin, USA, has been freezing slightly later at the end of each successive year, and like Lake Suwa in Japan and Lake Baikal in Siberia have been freezing later at the beginning of year. Ice forms first in the small shallow bays of Lake Baikal in late October to early November. This is the time when the lakes in northern Finland usually freeze. The major part of the north basin of Lake Baikal normally freezes over in early December, at the same time as many of the lakes in the Finnish lake district. To the South of Finland, freezing occurs later, as can be seen from data from southern Sweden (Eklund 1999). Lake Mjøsa in SE Norway also has a late freezing date, and 29 winters without ice cover have been recorded there over the period of 1864-1998. The period at the beginning of the 20th century was relatively warm and during several winters there was no ice cover. Lake Constance on the border between Switzerland, Germany and Austria has frozen only during periods of very cold winters - in the 20th century only once (in 1963). The same winter was also very cold in Finland. Lake Constance is very deep and its large volume prevents ice from forming. More shallow lakes in the area typically have an ice cover. Ice break-up can also occur differently in different climate zones. On Lake Baikal ice break-up occurs only slightly earlier than on lakes in Finland. On Lake Mendota the ice break-up occurs already about one month earlier than most of the lakes in Finland.

Statistics describing the global ice data are given in Tables 1-4 (Kuusisto and Elo 2000B). They present the longest series available from the 20th century for lakes from different regions. Their data were further analyzed in this study in order to study their usability for modelling and applications. Most of the ice data were collected in cooperation with LIAG, and in Article III, the comparisons of the ice models were made with the help of that data. The same data were used in Article IV in a discussion of the use of ice data. At times the winters were so warm that no ice cover formed. Both the ice data and the meteorological data indicate such a period during the first part of the 2oth century in Finland. It was also clearly visible in data from Lake Mjøsa where during that time there were several years when the lake did not freeze at all. Data from the southernmost of Sweden part were very complicated and have very large variability. Eklund (1999) has attempted to relate surface area, depth and altitude to ice dates in Sweden. In the northern parts freezing was highly correlated with depth, but not in the South. She found three lakes close to Lake Vättern with the very same ice break-up dates but with different elevation, surface area or depth, however freezing dates of those lakes had practically no correlation. The lakes had a rather similar surface area (15 km^2 and 11 km^2) and the same mean depth (5 m). The third lake had an area of 132 km^2 and depth 17 m. Elevations varied between 85 m and 220 m. Eklund found different mean values for different 30-year averaging periods. In many cases, 1931-1960 was warmer than the previous and the later 30-year period. Moberg (1967) has presented figures showing that during the rather warm period of 1929-1950 there were some relatively cold years. Data for Lake Mjøsa also showed relatively cold winters for the years 1939-1942 in the middle of an otherwise rather mild period. Some trends during the entire period are given in Table 4. Article VII also included some shorter series, but typically the longest possible series were considered.

Table 1. Freezing dates. The years of the extremes during the 20th century are given in parentheses (Kuusisto and Elo 2000B). (Absolute value of SD is given.)

	Suwa (Japan)	Baikal (Russia)	Kallavesi (Finland)	Näsijärvi (Finland)	Oulujärvi (Finland)	Mjosa (Norway)	Mendota (USA)
Average	Jan 9	Jan 11	Dec 3	Dec 16	Nov 19	Feb 15	Dec 23
Earliest	Dec 1 (1948)	Dec 19 (1910, 1947)	Nov 4 (1962)	Nov 7 (1910)	Oct 22 (1902)	Dec 30 (1919)	Dec 3 (1929)
Latest	Feb 7 (1934) 6 years no ice	Feb 6 (1959)	Jan 27 (1930)	Jan 30 (1930)	Dec 24 (1929)	Mar 5 (1971) 26 years no ice	Jan 30 (1932)
Range (d)	68+	48	84	87	63	65+	58
SD (d)	16	11	14	16	12	24	10
Skewness	0.6	-0.1	0.6	0.4	0.4	0.0	0.6

Table 2. Ice break-up dates. The years of the extremes during the 20th century are given in parentheses (Kuusisto and Elo 2000B). (Absolute value of SD is given.)

	Baikal (Russia)	Kallavesi (Finland)	Näsijärvi (Finland)	Oulujärvi (Finland)	Mjosa (Norway)	Mendota (USA)
Average	May 2	May 13	May 7	May 23	March 28	Apr 2
Earliest	Apr 17 (1923)	Apr 20 (1921)	Apr 16 (1990)	May 2 (1921)	Feb 3 (1964) 27 years no ice	Feb 27 (1998)
Latest	May 19 (1992)	Jun 1 (1909)	May 30 (1909)	Jun 11 (1909)	May 20 (1924)	Apr 20 (1923)
Range	32	41	44	40	107	52
SD	7	8	9	8	43	10
Skewness	-0.1	-0.1	-0.1	-0.1	-0.6	-0.5

Table 3. Ice-cover durations. The winters of extreme ice-cover duration during the 20th century are given in parentheses (Kuusisto and Elo 2000B). (Absolute value of SD is given.)

	Baikal (Russia)	Kallavesi (Finland)	Näsijärvi (Finland)	Oulujärvi (Finland)	Mjosa (Norway)	Mendota (USA)
Average	111	162	141	185	55	101
Shortest	72 (1958-59)	115 (1929-30)	79 (1929-30)	146 (1929-30)	0 (21 times)	47 (1997-98)
Longest	138 (1947-48)	197 (1940-41)	188 (1901-02)	219 (1940-41)	136 (1916-17)	126 (1903-04)
Range	66	82	109	73	136	79
SD	13	16	20	15	45	15
Skewness	-0.4	-0.2	-0.6	-0.2	0.0	-1.0

The statistics show similar changes for almost all of the lakes: duration of ice cover has become shorter especially due to later freezing. Break-up has also occurred earlier for all other lakes besides Lake Baikal. Lake Baikal has experienced the clearest change due to much later freezing, with 99.9% significance. Lake Oulujärvi, which is also located in a cold area, has also large deviations. A study by Magnuson et al. (2000) found trends based on lake ice data for the period 1846-1995 from the Northern Hemisphere: freezing occurred on the average 5.7 days later after 100 years and break-up 6.3 days earlier, translating 1.2°C warmer air temperatures per 100 years. An increase in variability since 1950 has also been observed.

Table 4. The changes of ice variables according to linear regression models (in days; a minus-sign denotes to an earlier and a plus-sign denotes to a later occurrence of the phenomenon during the 20th century (Kuusisto and Elo 2000B). Statistical significances at the levels of 95%, 99% and 99.9% are shown with one, two and three asterisks, respectively.

	Baikal (Russia)	**Kallavesi (Finland)**	**Näsijärvi (Finland)**	**Oulujärvi (Finland)**	**Mjosa (Norway)**	**Mendota (USA)**
Freezing date	+16***	+3	+3	+10*	+13	+6
Breakup date	+2	-4	-4	-8**	-22	-6
Duration	-14**	-2	-8	-16**	-27	-8

3.3.5. Measurements and observations of light conditions in water

Light is strongly absorbed by snow. As mentioned above, in southern Finland the snow cover is typically melted when ice is still 30 cm thick. Only small amounts of light can penetrate ice that thick. The low transmission of light in snow was observed also by Bengtson and Svensson (1996) and Leppäranta et al. (2003). Bengston and Svensson (1996) studied Swedish lakes, mostly in central Sweden. Ice thickness was usually over 30 cm. They noted that in spring, when light heats water, heat flux into ice increased. Leppäranta et al. (2003) studied lakes in Estonia (one measurement point was in the Gulf of Finland) during a very mild winter, when ice was no more than 30 cm thick. Wetzel (2001) also reported that under ice the top layers of water could be several degrees warmer due to heating by short wave radiation. However, ice melts soon after water is heated by light; direct heating from above is stronger. In southern Finland the melting of ice was well under way by the time the snow had melted.

The same extinction value was used for winters as was used for summer. The extinction coefficients used here were determined according to secchi depth observations, except in Article V, where they were determined with underwater light measurements. The values were used successfully in the calibration of the model application in some cases (Article VI), but often the model was more sensitive to other factors.

The so-called Secchi disk is usually a white, round plate with a diameter of 20 cm. It is lowered, and the depth where it is seen to disappear is the so-called secchi depth. The disk should be lowered so that no sunlight strikes in directly. With this method it has been possible to collect information from waters over long periods. On the other hand such observations are subjective and drone to various errors.

Inside the water, 400-700 nm has been determined to be effective for photosynthesis (PAR, the Photo synthetically Active Radiation). Then η has a value of 0.42 (the band 700-800 nm is assumed to be absorbed already at the surface of water). As the PAR band can be detected by the human eye, PAR attenuation is often determined with Secchi disk observations. The depth light penetrates is called the euphotic zone, which absorbs 99% of the radiation. The optical properties depend on the contents of the water. There can be large differences even in neighboring lakes. Optical properties of the boreal lake waters have been studied e.g. by Reinart et al. (1998), and in comparisons with oceanic water types by Jerlov (1976). Arst et al. (2002) further analyzed different types of lakes based on measurement data from Finnish and Estonian lakes. It has been found that in clear Alpine lakes the productive layer can be 2-3 times deeper than the secchi depth. Nordic waters are typically dark and the productive layer depth is about the same as the secchi depth; in the clearest waters in Finland it can reach only twice the secchi depth (Eloranta 1978).

The effectiveness of energy used in photosynthesis is typically 1-2% of the whole PAR energy range based on studies of several Northern American lakes (Wetzel 1975). About the same effectiveness was also found by Kaczmarek and Dera (1998) for the southern Baltic Sea. For the littoral zone in shallow lakes the effectiveness can be slightly greater, but usually the amount is ignored. There are other factors, including the amount of nutrients limiting and controlling photosynthesis. Under some very special conditions, blooming can be extensive and the vertical illumination profile can be affected, which can also affect the temperature profile.

Light inside water in each waveband was measured for Lakes Råksjö and Tämnaren in the summer (Article V) at the surface and at different depths. The extinction coefficients were determined. Several measurements were made during the summer at Lake Räksjö, but no large differences were observed there. The water in both of the lakes was rather dark, and the measured extinction was very similar. Nevertheless, their waters were clearly different from each other. The observed secchi depth was about 1.8 m for Lake Råksjö, varying by about 20 cm according to the season. Lake Tämnaren is very dark and a secchi depth of 0.5 m was typically obtained.

Some data were also available for a number of small lakes around Lake Pääjärvi, including temperature soundings. Rask, Arvola, Metsälä and Similä collected data in 1985 and 1986 (unpublished). Another set of sounding data by Huitu and Mäkelä (also unpublished) was available, including secchi depths. These data were collected during the summer season in 1997, some already early in the beginning of spring. In the shallow lakes, about 1 m and less, the bottom was visible except in one lake. The average secchi depth was about 2 m, with a maximum of 5.5 m and a minimum of 0.2 m.

Because these lakes are located so close to each other, the weather is very similar over them. Measurements were made during excursions lasting only for a few days, and the temperature soundings give an approximate description of the vertical structure at that time. Measurement periods for the excursions by Rask et al. in 1985 were from 11-12 July, 16-18 July and 25-29 September.

On 11 July, the wind speed was about 4 m/s in the afternoon; the next day was calm with a maximum wind of about 2.6 m/s in the morning. Both of those days were sunny and warm, with some clouds at mid-day, and air temperature rose above 23°C.

On 16-18 July, air was on the average about 2.5°C cooler than the previous period, with the maximum of about 19°C at mid-day on 16 July. The days were cloudy and humid with average wind slightly over 2 m/s. Air temperature, relative humidity and wind remained rather the same during the nights, but the first night was very calm.

On 25-29 September the air had cooled to an average of 5.9°C. The cloudiness was typically about half the total coverage, but the night between 26-27 September was clear and very calm, and air temperature dropped close to 0°C. The following night was also calm, but very cloudy and the air temperature was around 6°C. The average wind velocity was 3 m/s, with a maximum of 7 m/s on the evening on 28 September.

3.3.6. Micrometeorological measurements

Micrometeorological measurements above the lakes were used to estimate the horizontal variations of the meteorological fields above Lake Råksjö and Lake Tämnaren. Venäläinen (1998) has compared the measurements over Lake Råksjö and Lake Tämnaren with results of a theoretical model of a spherical lake. In this study the data are further considered for one-dimensional modelling. Venäläinen et al. (2003) continued studying the distribution of winds over a very fragmented lake using a program designed for the analysis of flow perturbations.

Measurements from 1994 were the first in the large field campaign and they were the first to be used to study the model application. In 1995 measurements were made throughout the summer, and they started when Lake Råksjö was not yet stratified. The measurements together with the model applications are described in Article V. The micrometeorological data were recorded at 10 min intervals. Fine resolution was needed to determine the rapid variations occurring in the air. Finer data were used in comparisons and studies testing the output. Eddy covariance data were measured over Lake Tämaren and compared with data from the meteorological mast in Märsta over the height of 100 m close to the lakes (Haldin and Gryning 1999). It was possible to estimate the spatial variation of the surface temperature for Lake Tämnaren with aircraft measurements on 13, 14 and 21 June 1994. According to the data 14 and 21 June were windy days, when some of the ten minute means for wind speed at a height of 4 m were above 10 m/s. A cold front passed the float on the afternoon of 14 June, as seen in a sharp drop in air temperature. There were not many clouds as can be seen from global radiation measurements. The morning 21 June was quite clear, but on 13 June there were cumulus and cirrus clouds. However global radiation measurements showed little cloud cover on 14 and 21 June.

3.4. Case study lakes

3.4.1. Finnish lakes

There are 187,888 lakes in Finland with a surface area larger than 500 m^2 (Raatikainen and Kuusisto 1990). The number of small lakes is large, but due to their small area the lake surface area is concentrated in larger lakes. Lakes cover 9% of the surface in Finland, but in the lake district in southern Finland 20% of the area is covered with lakes. Most of the Finnish lakes in this study are located in southern Finland. The first lake studied was Lake Pääjärvi (Article I).

Table 5. Surface areas of lakes in Finland (Raatikainen and Kuusisto 1990).

Surface area km^2	Count	Total surface km^2
<0.01	133,000	341
0.01-0.1	40,309	1,330
0.1-1	13,114	3,934
1-10	2,283	5,703
10-100	279	7,227
100<	47	14,128

The effects of climate and morphology on temperature conditions were further studied by constructing model applications as systematically as possible. It was possible to find morphologically different lakes with enough data to create models. These lakes are described in Table 6. Lake temperature data were necessary for calibrations, at least for the summer season adjustments. Summer stratification is highly sensitive to wind. For winter season studies, ice observation data were needed for control purposes. Ice observations for almost all the lakes selected had been included in the LIAG data set. Climate has the strongest effect on small lakes; the ice cover of some small lakes were studied even if summer season data were lacking. If these data were missing, these lakes could not be included in the study of summer seasons. The ice data were not available for some of the small lakes, they could not be included in the winter season data. The transfer of the data for nearby lakes resembles downscaling of coarser climate model.

Lake Pääjärvi and Lake Valkea-Musta have also been involved in EU's REFLECT-project, which focused on the biological features of lakes and their regional effects in connection to climate inside Europe.

Table 6. Finnish lakes with long-term study data. Data for summer or winter or both seasons were considered (based on available data). Lake Pielavesi and Lake Nilakka are treated together, and their surface area is the sum of the surface area of both basins.

Lake	Season	Area km^2	Maximum depth m	Location
Lake Pääjärvi	summer, winter	13	85	61°04’N, 25°08’E
Lake Valkea-Musta	summer	0.14	10.5	61°13’N, 25°07’E
Lake Vanaja	summer	109	24	61°10’N, 24°10’E
Lake Jääsjärvi	summer, winter	65	20	61°37'N, 26°08'E
Lake Näsijärvi	summer, winter	257	51	61°32'N, 23°45'E
Lake Kallavesi	summer, winter	887	71	62°50'N, 27°40'E
sub-basin		41	50	
Lake Koivujärvi	winter	26	16	63°28’N, 26°15'E
Lake Kiimasjärvi	winter	3,8	19,5	62°37’N, 25°32’E
Lake Pielavesi (Lake Nilakka)	winter	270	31	63°20'N, 26°32'E (63°08'N, 26°33'E)

Lake Valkea-Musta is an example of a small, sheltered lake. Many observations and measurements were available, because the lake has been extensively studied by the Department of Geophysics, University of Helsinki.

The shape of Lake Vanaja is very complicated. The water level is strongly regulated, and the average yearly change is about 1.5 m. It does not stratify as strongly as the other lakes and sometimes overturn occurs during summer. The lake is heavily loaded by industry.

Lake Jääsjärvi has been studied as an example of a complicated basin system. Thermistor chains have been placed in the main basin. Much of the lake is shallower than the thermocline depth during summer. Due to the darkness of the water, heat is absorbed at the top layers, and sheltering often increases warming: the water is rather calm. The hypsography expressed as precentage of the main basin, (Harjunselkä), resembles that of the whole lake. The lake is unregulated and remains in rather natural condition. Throughflow is strong.

Lake Näsijärvi has also many basins with complicated shapes, but three main basins predominate. In Finland geological processes have often formed deeper basins perpendicular to each other, and many lakes have such crossing basins. Internal waves can be excited in them, but their broken complicated shapes can prevent the formation of standing waves. The hypsography of all of the Lake Näsijärvi is similar to that of the south sub-basin, where the temperature observations were taken. The maximum secchi depth can be as deep as about six meters, but calibration showed that the secchi depth of about two meters could be used for Lake Näsijärvi as well. Its mean depth is 14.1 m.

Lake Kallavesi is the fifth largest lake in Finland. It has many sub-basins of considerable depth. There is water exchange between the basins, potentially complicating the temperature structure, but that was ignored. Because it was not possible to adjust the model for the lake, the main basin southeast of the city of Kuopio was chosen. Ice observations and temperature soundings have been made there, and they represent the basin well.

Lake Koivujärvi has broken shores, almost separate basins and several rather large islands. The dynamics in the lake basin are very complicated. The landscape around the lake is rather flat, and the lake bed is rather uniform. Horizontal variations were not considered for this lake, because water temperature data were not available for calibration and verification. The ice seasons were studied here, because it is one of the small lakes hypsometry is known and for which long series of ice data are available.

Only winter ice periods of Lake Kiimasjärvi were studied for same reasons: ice data and hypsography were available, but temperature recordings were not. Lake Kiimasjärvi is even smaller than Lake Koivujärvi, it is deeper and its shores are steeper. It has roughly two crossing basins. The surrounding landscape has similar forms, but the hills are not very high. It was obvious that shading had the most important effect, and wind had to be reduced strongly for the model application.

Winter seasons of Lake Pielavesi-Nilakka were also discussed in Article VII. Both parts of the twin lake system have bays and islands. These forms were created in phases during glaciation, and the basins are also oriented roughly from north-west to south-east. Some surface temperature measurements from the sound connecting the basins could be used for the application.

Lammi Biological Station, University of Helsinki, is situated on the northern shores of Lake Pääjärvi. The Evo Game Research Station is a little further to the north, in an area with a lot of small lakes. The area has also been studied by Brofeldt (1920) and Arvola (1986). Data were available from the year 1997 from 18 small lakes in Lammi and from 10 in the neighboring municipality of Tuulos. These lakes were typical of small lakes in the area, only some of them having a surface area larger than 5 km^2. Their average depth was 8 m, and the maximum depth was 29 m. Some lakes were only one meter deep, some even less.

3.4.2. Other northern European lakes

Two small lakes in Sweden were studied in Article V. There are located in conditions, which are very similar to those in southern Finland. Lake Tämnaren (60º00’N, 17º20’E) is rather large and shallow: its surface area is 37 km^2 and its maximum depth is 2 m. Lake Råksjö (60º02’N, 17º05’E) has a hypsographic curve resembling a conical hole. Its surface area is 1.5 km^2, maximum depth 10.5 m, and the mean depth 4.3 m. The lakes are surrounded by a rather typical boreal landscape with forests and agricultural areas with no high hills (Haldin et al. 1998).

3.4.3. Lake Mendota

Lake Mendota, Wisconsin USA (43°07'N, 88°25'W), has been studied in many classical lake studies (Hutchinson 1957). Its surface area is 39.1 km^2, mean depth 12.4 m and maximum depth about 25 m. The PROBE model adjustment was made using meteorological input data that had been used for a model application with the LIMNOS model. No further modifications or calibrations were necessary other than to calibrate radiation data according to measurements. Ice cover periods were studied by calculating freezing and break up dates and ice thickness. Precipitation was also considered because it is more important in those continental conditions.

3.4.4. Lake Constance

Lake Constance is located in Central Europe (its midpoint location is 47°39'N and 9°18'E). A general description of it has been given by Bäuerle and Gaedke (1998). The lake has three basins, and its total area is 534 km^2. The Rhine flows into it from the Alps. A deep sound (about 100 m) unites the northernmost basin (Lake Überlingen) with the main basin (Upper Lake Constance, surface area 472 km^2, mean depth 101 m and maximum depth ca. 253 m). The third basin is the rather small and shallow Lower Lake Constance (surface area 62 km^2, mean depth 13 m and maximum depth 40 m), and the Rhine flows out from the western side. The climate of the area around Lake Constance is also continental, but not as severe as in Wisconsin, USA. Due to its southern location and great depth, ice formation is very rare: according to Magnuson et al. (2000) the main basin freezes only in the coldest years.

4. Results

4.1. A sensitivity analysis of a temperature model of a lake examining components of the heat balance

The PROBE lake model was developed using lake data. The sensitivity of the model to differences of surface forcing was studied by comparing the results of the model application with earlier determinations of parameters based on lake measurements and the water budget method. The model was able to give a good areal estimate of lake evaporation and to compute components of the heat balance. It was possible to calibrate the model by multiplying the wind velocity by a suitable factor.

4.2. The effects of climate change on the temperature conditions of lakes

SILMU scenarios were used. With Lake Pääjärvi transient scenarios were used: the baseline climate was modified by adding the scenario changes as they were Pjojected to occur over a long period. Averages and the standard deviations of the temperature parameters in the changing climate were computed for the years 2036-2065. For the year 2050 (June August) the surface temperature increased by 1.8°C, with low and high projected increases of 0.5°C and 2.6°C. All the results showed significant changes in the temperature regime, e.g. increases of 30-60 days were predicted in the length of stratification and the ice-covered period. The non-continuous ice-covered periods that were simulated may also indicate periods of partial ice cover.

4.3. Ice modelling calculations, a comparison of the PROBE and LIMNOS models

A PROBE model application for Lake Pääjärvi in Finland and a LIMNOS model application for Lake Mendota in Wisconsin were compared. Data from the same baseline period 1961–1990 were available for both lakes. It was possible to exchange their data and make applications for model comparisons. For that purpose, snow cover was also modelled separately with the PROBE. Observed and simulated dates of ice formation and break-up corresponded to each other, as did also ice thickness and snow cover. This correspondence could be improved with a more detailed description of mixing, especially regarding spring and autumn results.

4.4. Lake and river ice variables as climate indicators in northern Europe

Old hydrological data have many pitfalls. Ice has become thinner during the 10-year period of the research. Maximum ice thickness, which is a measure of the severity of the winter, is a rather complicated function of snowfall and temperature. Even with exactly similar frost sums and snowfall totals, the maximum thickness of lake ice may vary considerably from year to year and lake to lake.

4.5. Energy balance and vertical thermal structure of two small boreal lakes the during summer season

It was possible to solve the terms of the energy balance, surface temperature and the vertical temperature structure of these small lakes. When horizontal variations were accounted for, it was possible to average the sums of the values of the components of the energy balance determined according to measurements with diminishing residuals for both of the lakes. With the same averaging, it was possible to solve for the vertical temperature profile using the models. The box model (the SLAB model) was also able to model the results, but diurnal information could not be obtained due to the time step used by the model.

4.6. Modelling of summer stratification of morphologically different lakes

The PROBE model was used with long series of meteorological input data from Central Finland (years 1950-1997). The effects of morphology were considered by applying the model to different kinds of lakes near the station. The data were recorded at an airport. The surface areas of the lakes ranged from 257 km^2 to 0.14 km^2 and maximum depths from 10.5 m to 85 m. Summer stratification periods were calculated successfully, but only after adjusting with data for each lake. Local weather differences cannot be taken into account using distant data, but systematic data changes were considered comparing distant data with the data from neighboring weather stations (used in SILMU). In lakes with a large area to depth ratio, heat is absorbed freely. When the ratio is small, heat tends to be trapped in the epilimnion. For very small lakes sheltering is essential, and a large total volume delays cooling. If the ratio of surface area to depth is large enough (for these lakes about 3-5 km^2/m), climate dominates and the lake can be heated. If the ratio is smaller (for these lakes less than 1 km^2/m), the small volume of the lake limits the heat intake, and the heat tends to be trapped in the epilimnion.

4.7. Long-term modelling of winter ice periods for morphologically different lakes

The long series of data from Jyväskylä were adjusted to model seven morphologically different lakes in southern Finland (years 1917-1950 and 1951-1997, data from the later period is more reliable, because they are obtained from automatic stations). Most of model applications were first calibrated with summer lake data. Some lake applications with long ice observation series were made by changing model parameters, and the output sensitivity was studied. The ice model was based on air temperature and was able to describe ice formation and break-up. It was possible to improve the suitability of the model for individual lakes by changing the factors for melting, ice breakage wind limit and the temperature limit for determining total ice formation. The freezing dates of the lakes are about one month apart. Differences in average ice break-up dates are small, within four days, and they are strongly influenced by air temperature. However, the model could even help to relate these differences to morphology. In the period 1917-1950 freezing occurred on the average four days later than 1951-1997, and ice broke up one day earlier. Deep lakes froze about one month later than the shallow lakes. It is hard to find clear signs of any effects of morphology on the timing of the ice break-up from the observed dates.

4.8. Results from the Appendix (Section 7)

The Appendix (Section 7) presents more details of the model applications for the lakes and data treatment made. The verifications of the models for the summer season (Article VI) provided additional evidence of the difficulties facing attemps to model both the surface temperature and the vertical temperature structure. Sheltering is essential for small lakes, and their small area further affects mixing. Often the vertical profile is observed to have a gentle shape: there is a metalimnion between the epilimnion and the hypolimnion. This has many important consequences for biology and chemistry because it facilitates the exchange over the vertical. The PROBE model can usually be adjusted by modifying the wind, in order to represent sheltering. The modelled profile is typically too abrupt. The importance of the right level of incoming radiation has been crucial in practically all applications. Many studies have found the optical properties inside water to be important, but calculations with the PROBE applications have typically shown that for the dark Finnish waters with small variations the effects were minor. However, for Lake Constance, which is a deep lake, calculations showed large effects, especially for winter, even if the water was not clear. There can also be important local climate variations, which cannot be described with data from a distance, varying from year to year. The effects of these variations on the lakes can also vary from very modest changes in temperature of the epilimnion to overturn during season when stratification usually prevails, depending on climate conditions and the morphology of the lake.

The Appendix (Section 7), includes also an empirical model of the heating of the hypolimnion, based on data from a number of small lakes (surface areas smaller than 0.45 km^2). Some of the small lakes were stratified, while the rest were already mixed. It is difficult to create an average temperature profile that succesfully desribes the whole group. Efforts to model these small lakes with a model like the PROBE run the risk of beeing severely compromised by their limited area. The results of this model are compared to those obtained with the PROBE model. Although the empirical model is calibrated with data from smaller lakes, the results are comparable to those obtained with the PROBE for lakes with smaller surface areas, even in the case of a deep lake like Lake Pääjärvi (surface area 13 km^2). Lake Valkea-Musta (surface area 0.14 km^2) was modelled with both of the models. However, measurements showed unusually strong mixing there, compared to the other small lakes.

Some comparisons of the PROBE results for Lake Jääsjärvi (Article VI) were made with obtained with those obtained with an application of the distributed watershed model HBV, including a simple lake model. Surface temperature and ice cover were successfully computed with the HBV application, but they were most exclusively affected by air temperature, due to their formulation in the model. The spring results were mainly affected by air temperature and the models gave close break-up dates. For freezing. The PROBE model was more succesful in simulating the effects of depth, but the HBV application gave on the average the same difference between observed date and calculated date, determined as the first onset of ice. The final date usually used for defining the freezing date is much later (22 days in the Appendix). This must be due to the calibration of the whole large HBV model system, which makes the interpretation of the sub-models problematic.

5. Discussion

The use of a one-dimensional approach for modelling lake temperature features was studied. The main temperature features - the vertically stratified water temperature during summer and ice cover during winter - can be described to a large extend with the one-dimensional approach. These features are controlled by the climate, but the morphology of the lakes, primarly their different sizes and shapes, have their effects. However, these effects can also be taken into account succesfully with the one-dimensional model approach. For vertical resolution a turbulence model was used, although for its use the horizontal dimensions have important limitations. For analyzing these, a collection of morphologically different lakes was selected. Meteorolological input data from the lakes and data from synoptical stations over land were analyzed, with varying scales of time and distance. The turbulence model was compared with models with only one or two layers of water as well as with a one-layer model inside a hydrological watershed model. The results that can be compared are the water surface temperature (during winter the ice cover). The long ice cover series were also studied to obtain additional statistical information. The turbulence model was also used to study the effects that can be projected to occur due to the hypothesized climate change. When connecting models with varying dimensions, solving the whole energy balance is increasingly important. In many earlier methods the whole energy balance has been used when calculating an individual component, and this, in turn, has affected model parameters.

Hypolimnetic heating was studied in some very small lakes, and the results of the empirical model based on the observations were compared to those obtained in some of the lakes modelled with the turbulence model: for the smallest of them the results were still acceptable. The heating of the hypolimnion is an important factor that is connected to the formation of the metalimnion, the layer where the temperature of the warmer epilimnion decreases. When a purely one-dimensional model is used, the calculated epilimnion is rather isothermal, and temperature decreases rather quickly as an abrupt step. Lake volume decreases as depth increases. This modifies mixing in water, and at greater depths only smaller eddies have room to exist. Shore characteristics also influence mixing by changing the field of the meteorological input over the lake and the movement of the water in the lake basin. The use of seiche waves in the turbulence model was described by Svensson and Sahlberg (1989). The model was first applied to Lake Pääjärvi using data from the lake. The model was adjusted so that it would give essentially the same results with and without the use of the seiche routines. The deep-mixing routine was found suitable.

The solving of the energy balance was complicated by the fact that an earlier study (Elomaa 1977) used the obtained residual in order to compute the rate of the change of the heat content in the lake, but the measured temperature profiles gave a different result. This has often been explained with advecting heat, which can be very important, especially in large lakes with larger volume and thermal inertia. Rather large residuals were observed for

Lake Valkea-Musta, according to the values obtained with lake measurements. Additional analyzes of Lakes Råksjö and Tämnaren with detailed data made it possible to average the residual close to zero over longer periods, when horizontal averaging was taken into account (Article V). It is also mentioned that some results concerning evaporation from small lakes show that they can increase evaporation through advection. Other results indicated decreased evaporation through sheltering, e.g. Gorham and Boyce (1989) for several small lakes in Northern America, Europe and Japan, and Fee et al. (1996) for Ontario, Canada. Fee et al. also studied some streams with regression analysis to relate their surface temperature to the air temperature from the point of view of global warming (Mohseni et al. 1999). Williams et al. (2004) used regression and factor analysis to study ice cover. The possibility of using a turbulence model like the PROBE increases the possibilities to compare and analyze the results for small lakes and rivers with all the statistical data available, and additional evidence and support can be obtained with numerical results.

The model for Lake Pääjärvi was also used to analyze the effects of changing climate. The same turbulence model was used for four additional lakes with different approaches in order to analyze climate change. Lake Lappajärvi, formed in a meteorite impact crater, has a surface area of 161 km^2 and a depth of 41 m. Lake Längelmävesi has a very fragmented and broken shape due to its many islands. Its surface area is 11.2 km^2 and its depth is 41 m. Lake Kalliojärvi is a small lake with a surface area of 0.25 km^2 and a depth of 13 m. It is affected by forestry. Lake Sarmijärvi, located in northern Finland, is also small, with a surface area of 4.6 km^2 and a depth of 27 m. Theoretical consideration was given to the effects of geographical location by varying simulations of a hypothetical lake in various parts of Finland. In all of these simulations, substantial reduction were estimated for the ice cover period, as well as for successive periods with and without ice cover, with the possibility of partial ice cover. It was more difficult to generalize the results of the calculated temperature profiles. Morphology was seen as the most likely explanation: lakes can have different responses to climate due to their different morphologies.

The models for Lake Kalliojärvi and Lake Längelmävesi were also used to analyze the effects of climate change on eutrophication (Frisk et al. 1997), adding separate equations for nutrients and including a description of pelagial plankton growth. This water quality model is first calibrated to calculate water temperature. The results are strongly dependent on catchment development and the amount and type of nutrients in the inflow. Frisk et al. (1997) concluded that in addition to the increased risk of eutrofication, the spring phytoplankton peak can be estimated. This method increases the importance of modelling springs, but unfortunately it has often been impossible to start the field studies until later in summer and it is not easy to find necessary data.

Usually the isothermal period in spring is not long and stratification can take place even without an isothermal phase (Wetzel 2001). Kuusisto (1981) has noted that in Finland summer stratification can take place without an isothermal period. Some monomictic lakes in the Evo region have no spring turnover, but most of the lakes there do have it (Arvola 1986). The importance of spring conditions will increase also in Finland if the climate is warming, but presumably radiation in spring may be increased only if cloudiness is reduced. Less snow on ice is often predicted, and warm air and precipitation as rain will further reduce snow accumulation. Horizontal effects may also be caused by density differences in cool spring water in larger lakes, as discussed by Malm (1995) among others.

Description of density of water should perhaps be modified under some circumstances. Density effects become important in lakes about 100 m deep. The density formula is based on a temperatur of 20°C. When water temperature is close to the maximum density temperature of 4°C, especially in spring, it may be important to modify the density formula. The contents of lake water may also have some important effects, especially on the absorption of light.

Black ice can transmit light relatively easily, as noted by Bengtson and Svensson (1996) and Leppäranta et al. (2003). Leppäranta et al. (2003) noted under-ice thermoclines in Estonian lakes at the depth of two to four meters, rising to about 1.5 m to March. The study by Bengtson and Svensson concerns Swedish lakes, mostly in the central part of Sweden, where the ice thickness was usually over 30 cm. The latter study included some Estonian lakes during a very mild winter, when the ice was no thicker than 30 cm. Bengston and Svensson also studied heat fluxes and noted that during spring, when light heats water, heat flux to the ice increases. Modelling in this study is focused on the use of meteorological data for lake applications, and for winter applications ice cover was the main target. However, according to the calculations, heating is already substantial in May (e.g. Appendix 7.4 and 7.5).

After SILMU some additional climate scenario versions have been made. Calculations with them (Elo 2002) produced results that were comparable with previous results reported by Elo et al. (1998). Some more precise estimates concerning winter periods were included in the scenarios. These provide further evidence that warmer winters can be expected with increasing probability. This, in turn emphasizes the importance of developing the model for winters with cool open water and periods with partial or discontinuous ice cover. Such models are better suited to the study of those conditions.

The effects of changing climate were studied within the larger SILMU program and the time period was determined accordingly. However, 30 years is regarded as the minimum for several statistical parameters (e.g. Yevjevich 1972). To further analyze the effects of morphology, basic information was obtained for a variety of lakes. As several different factors affect climate, long data series of several variables were needed for a selection of morphologically different lakes. Often long series are available only for air temperature: meteorologists have strict criteria for their data. However, the data may be good enough to be used for modelling, even if they are not always of the best possible quality. The demand for optimum quality may severely limit the possibilities of finding enough suitable data. This is perhaps most likely to be the case for wind data, due to the observation methods and changing environments (Article VII). For this reason modelled wind data have been used in some studies. It was possible to use data collected by the city of Jyväskylä for a selection of morphologically different lakes in the vicinity. The data coverage was then expanded even further to gain as long a modelling period as possible: data for a period of 40 successive years summer seasons and 80 successive winter seasons were obtained (with only one year missing). The data were transferred to the lakes modelled in a way that resembles downscaling of climate model scenario data. Changing the meteorological input data had an important consequence for the model. In earlier applications for Lake Pääjärvi the transferred humidity and air temperature data were modified based on lake data. When the longer data series were used for these diverse lakes, it was not possible to estimate conditions separately for each lake. It was possible to adjust the data for all of the lakes, but the deep-mixing routine was no longer suitable for Lake Pääjärvi. The deep-mixing routine was tested for the other lakes as well, but the results were unacceptable. In some studies the turbulence model parameters have been adjusted to account for additional mixing e.g. by seiches, as was done by Goudsmit et al. (2002). Fang and Stefan (1996) determined the vertical thermal diffusion coefficients for their model using field study data from another lake. In this study an effort was made to avoid empirical fitting as much as possible in order to achieve results that can be generalized.

The long series of ice data were also analyzed in order to determine their usability for modelling and for statistical analysis of lake temperature conditions. The series are included in the LIAG database and they have been studied regionally, comparing them with data from numerous other lakes in the vicinity. A study by Assel and Robertson (1995) concluded that the use of cumulative air temperature in climatological analyses is not enough for calculations of freezing and ice break-up. For exact timing, daily and even shorter interval data are needed. They mention particularly air temperature and wind speed. They defined freezing as the moment of first occurence of ice cover. The same method was used for Grand Traverse Bay, which is affected by heat currents from the main body of Lake Michigan. In several years ice did not form there or there was ice only for short periods of several days. Lake Mendota is located further to the south than Grand Traverse Bay, but ice has always formed on it (in the present climate). Recently the ice cover has been forming relatively late and for shorter periods, which also shows tendency towards milder winters there.

Vavrus el al. (1996) have studied Lake Mendota, together with some other nearby lakes with different depths using the numerical LIMNOS model. They were satisfied with the results for autumn cooling obtained for lakes of different depths with their two-layer model for water. They pointed out that it was impossible to account for variations between different lakes having different surface areas with a purely one-dimensional model with uniform climate data, because the importance of heat absorption, among other factors, along the shores can vary for each lake. The LIMNOS model was compared to the PROBE model in Article III, especially the ice model and the calculated ice. In spite of all the differences in climate conditions it was possible to adjust both of the models for both of the lakes. In so doing the importance of adjusting properly for global radiation was noted, but otherwise it proved to be possible to use the model parameterizations and adjusting methods relatively straightforwardly for both of the lakes.

Data from North America and central Europe were also used with good results: it was possible to adjust the PROBE model with synoptical meteorological data and gain realistic results, even if ice was rarely formed.

Mild winters cause problems: a durable ice cover cannot form if the air temperature is close to 0°C. These periods are also problematic for ice cover modelling and should be studied further in order to obtain better estimates of ice cover during milder winters. In present climate conditions the ice model can be improved with rather simple model parameter modifications related to the physical conditions of the lakes, their location and morphological features: wind limit for ice breakage, water temperature limit for determining total ice coverage and the melting factor. In principle, this can also help to resolve differences in the data based on morphological features.

The results obtained from water surface temperature modelling were further compared to those obtained with a distributed hydrological model (HBV). It was possible to use a HBV version including a lake surface water temperature routine of one of the lakes that was also modelled with the PROBE application. The results were rather good, but comparison with observations showed that further improvements would improve accuracy and comparability. The description of springtime with the HBV model was too simple, and there were large differences between the calculated temperature and the observed temperature, especially for some years. Although the HBV model is calibrated using surface water temperature in summer, the temperature remained too low - possibly because the observation site was too close to the shore. The HBV model also smoothes the results due to the daily time step, as with the SLAB model. Cooling in late autumn also took place very slowly. The HBV model, like the PROBE model, gave successive periods of freezing and open water for mild winters. According to the HBV model results, ice forms with when the first onset of sub-zero temperatures. The PROBE model results are close to the final date of full ice coverage, which is defined as the observed freezing date. With the PROBE model, the stored heat can delay ice formation. Although the HBV model can include a description for heat stored in the lake, air temperature determines freezing strongly, and the whole model system is calibrated using water surface temperature close to the shore and meteorological input data over land. This effect of depth on freezing was about 22 days, which is considerable; the lake modelled was only 20 m deep.

Further model development should address the role of UV radiation, which was broadly reviewed by Booth et al. (1997). The observed increase is strongly related to geographical location and local conditions. Its effects can be relatively strong on global warming Via marine production; although freshwater water bodies represent only 0.5% of the water surface their ecosystems were found to be excellent for model studies. UV radiation has been found to be related e.g. to dissolved carbon and PAR radiation, in Canada (Laurion et al. 1997). In Finland the effects of UV radiation on fish especially in springtime were found to be very important, but the risks of harmful effects caused by future UV climate on populations of vendace and whitefish have been estimated to be small (Oikari et al. 2002). If temperature model applications for spring conditions are improved, the ecological effects could be analyzed more thoroughly by adding the effects of UV radiation on biological processes among other factors.

6. Conclusions

The most important features of the thermal behavior of the lakes can be described with a one-dimensional approach: water temperature stratifies during the summer and an ice cover is formed during winter. These factors and their strength are influenced by the climate and are related to the location of the lake and the local conditions. They provide the settings in which other physical features are observed and chemical and biological processes occur. However, morphological features have highly important effects, considering the shapes of the lake basins and dynamic and the climate over the lake, which is affected by the shore forms and the adjacent landscape. These can be described with one-dimensional models, also taking the lake energy balance into account, although the limited extent of most lakes has very important effects. It is import to solve the energy balance, because in principle that is requided in order to unite models with each other, using various scales and data.

The main lake model in this study was a turbulence model that could be adjusted for use on lakes of different sizes and depths: it also had vertical resolution, which is important in lakes due to the formation of the metalimnion, which affects the heating and motion of the hypolimnion. Many biological processes are strongly affected by these factors, which increases their importance for modeling success. Many lakes have complicated dynamics and shore forms, but in practice, it was necessary to take only hypsography and sheltering into account. Although lake data were still necessary in order to adjust the model, it was possible to model ice cover with data that had proven to be suitable with other models. This, together with the analysis of the ice cover data supports the wide applicability of ice cover modelling. Nevertheless, climate change is threatening to challenge its applicability, because ice cover will be strongly affected by milder winters and there may even be periods when the ice is melted totally. This may have strong effects on the basic physical conditions. Stronger winds are also been predicted. These may contribute to ice breakage, but most importantly the water would be mixed for much longer periods. This might have strong effects on many activities, from fishing to traffic. Not all of these may be negative, e.g. oxygen conditions may improve. Many potentially important factors are related to changes in the environment, e.g. nutrients in inflows. Although these rarely affect the main physical features, they may have important effects on the processes. For this reason it might be useful to develop the model accordingly. Although light conditions under the ice have been studied lately, descriptions of density close to the maximum could be improved, especially during winter in cold water. Possible changes in spring conditions have been regarded as especially important for models with ecological implications. Field measurements are inherently problematic in spring, particularly during ice break-up, and unfortunately few data are available.

7. Summary

One-dimensional numerical modelling has been developed into a useful method for solving the basic thermal features of lakes. The size and shape of the lake, and, above all, its volume affect the energy exchange, which is controlled by the meteorological conditions over it. The main thermal conditions are found to be related to the location and corresponding climate, but several additional factors enter in and cause differences. The main features are connected to the formation of ice cover and the stratification of water during open water periods. These can often be described with simple models related to surface temperature: during cold periods the water is frozen. During warmer periods the temperature of water closely follows air temperature. The thermal inertia is closely related to the volume and the heat exchange.

With a turbulence model for water, the PROBE model, vertical resolution can be obtained, but small lake size has important effects. Changes in the meteorological conditions can be given with rather simple modifications that can be thought to represent horizontal averaging and systematic changes according to location. The results obtained with the PROBE model were compared to those obtained with simpler lake model. Meteorological data for this purpose were studied over scales ranging from small scale turbulent fluctuations over the lake to series of synoptical data over one hundred years long. In general, Finnish lakes were studied, but direct comparisons were made with continental conditions in Northern America and Central Europe. Lake data were used to make the calibrations and for verification. Special attention was paid to analyses of ice cover, considering their usability for modelling.

Climate change has to be considered carefully; global warming is regarded as an important future development that will influence lake conditions. With the development of the models to include thermal features of lakes, their suitability in studies of ecological features will improve considerably. Especially the lack of ice cover will affect ecological conditions. Physical conditions may also change under the ice, and in principle these changes can be modelled with the PROBE model, too. However, in addition to modifications in the physical lake model, other changes may influence ecological conditions, flows of nutrients and other chemical constituents in water. Even changes in the composition of the radiation penetrating into water can affect the processes, although their effect on heating may be negligible. Such changes can also occur during summer, but the most important change predicted is the warming of the surface water.

Most importantly, improvements in the models of the physical settings make it possible to combine different models and data systems. The climate models can yield data for lake models, and the effects of lakes and lake systems on the local climatic conditions can be estimated. Advection of moisture is most important in dry conditions, but advection of heat may also be important because it is related to heat stored in the landscape. All these factors can be analyzed with numerical lake models. The PROBE model, which can give the important vertical temperature resolution, can also be used to solve the whole energy balance at the same time. The numerical results also facilitate the analyses of the statistics involved and comparisons of different conditions.

8. References

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7. Appendix

7.1. Lake Pääjärvi

Lake data were first used to adjust an application for the PROBE model (Virta et al. 1992B). From the beginning, the goal was to present the entire energy balance. The components of the energy balance, together with the various applications for Lake Pääjärvi made in this study, are presented in Tables 7-10. Table 11 and Table 12 give temperature at the water surface and at the depth of 2.5 m. The values given by Elomaa (1977) are based on lake measurements; however he presented the rate of the change of the heat content as a residual obtained with the surface fluxes. For purpose of comparison, data for the same period were generated using synoptical meteorological data from a nearby station (Article I). This application was further developed by Virta et al. (1996), and additional corrections were made for global radiation and wind by comparing data from Lake Pääjärvi with data from the synoptical stations of Utti and Jokioinen. This was done primarily to obtain longer baseline data. The application was then used by Elo et al. (1998) for calculations with climate change scenarios (Article II) with a 30-year baseline. An even longer baseline was obtained with synoptical data from Jyväskylä for the model in Article VI.

When data from a more distant synoptical station (Jyväskylä) were used (Article VI), the model for Lake Pääjärvi had to be modified. The earlier model used the deep-mixing routine, which made the shape of the temperature profile more gentle at the metalimnion. When the data from Jyväskylä were used the air temperature and humidity were not modified with the lake measurements, and the deep-mixing routine was not suitable. The application results were analyzed together with the other lakes using the same data from Jyväskylä in Article VI, , but the values given in Tables 7 -12 were not presented in the article and they give further information. The results were comparable to those obtained with the earlier applications. Usually, the July water temperature calculations were slightly too high, later they were slightly too low. The differences were larger during autumn and cooling. Relatively larger differences were typically found for autumn with input data from more distant meteorological station¸ but absolute values were larger during summer. The temperature fell further and more smoothly during cooling, and relatively large differences in the associated values were observed during the summer due to large water volume and sensitivity of the surface fluxes to surface water temperature. The modelled radiation balances were typically closer to each other and to the measured values during summer. Less heat entered into the water in September and more in October than what could be concluded according to the actual measurements. Modelled fluxes of latent heat and sensible heat were smaller later in autumn, although at the same time the calculated surface water temperature could be even closer to the measured values than during summer.

Table 7. Flux of latent heat *LE* (W/m^2) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

LE	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	126	90	103	104	88	91	95	103
August	100	108	104	94	92	80	80	81
September	85	83	84	69	79	81	76	65
October	42	41	42	27	47	40	39	25

Table 8. Flux of sensible energy *H* (W/m^2) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

H	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	26	15	15	17	13	18	17	19
August	35	24	21	23	27	20	19	21
September	33	35	33	31	40	38	34	32
October	21	25	24	17	22	24	24	16

Table 9. Radiation balance *R* (W / m²) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

R	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	-140	-168	-153	-156	-128	-130	-128	-145
August	-105	-115	-107	-108	-95	-92	-93	-77
September	-31	-29	-21	-17	-29	-20	-17	-17
October	6	27	24	22	0	26	21	21

Table 10. Rate of the change of the heat content *Q* (W / m²) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

Q	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	-13	62	35	35	27	21	16	23
August	-30	-17	-17	-9	-24	-8	-6	-25
September	-87	-88	-95	-83	-90	-97	-92	-80
October	-69	-91	-88	-65	-69	-88	-83	-62

Table 11. Surface temperature (T_s, °C) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

T_s	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	18.4	19.3	19.0	19.2	17.2	18.9	18.8	20.0
August	19.5	22.7	21.0	21.7	17.6	19.1	18.8	18.3
September	12.6	13.7	13.1	13.6	12.3	12.7	12.5	12.3
October	7.3	7.4	7.1	7.2	7.0	6.4	6.3	6.3

Table 12. Temperature at 2.5 m depth ($T_{2.5}$, °C) for Lake Pääjärvi. Values were obtained with the model application using data from Jyväskylä (Article VI).

$T_{2.5}$	**1969 Elomaa (1977)**	**1969 Elo (1994)**	**1969 Virta et al. (1996)**	**Value**	**1970 Elomaa (1977)**	**1970 Elo (1994)**	**1970 Virta et al. (1996)**	**Value**
July	18.5	19.2	18.8	18.9	17.9	18.8	18.6	19.7
August	19.5	22.5	20.8	21.2	17.6	19.0	18.6	18.1
September	12.8	13.8	13.1	13.6	13.1	12.7	12.5	12.3
October	7.5	7.5	7.1	7.2	-	6.4	6.3	6.4

7.2. Small lakes in the Evo District near Lake Pääjärvi

The data from the small lakes were grouped to describe average conditions from 11-12 July, 16-18 July and 25-29 September 1985. The lakes are very small and shallow, but rather large differences were observed in the average temperature profiles of the lakes. (1986 data from a set of lakes in the Evo District were not analyzed here, primarily because surface area and depth data were only available only for some lakes in that set.)

According to the measurements made on 11-12 July 1985, in four of the lakes the depth of the thermocline was about 1-3 m. Three of those lakes were shallower than 8 m deep: Lake Huhmari (maximum depth 8 m, surface area 1.6 $\cdot 10^4$ m²), Lake Rieskalampi (maximum depth 4 m, surface area 2.5 $\cdot 10^4$ m²) and Lake Mekkojärvi (maximum depth 3 m, surface area 0.3 $\cdot 10^4$ m²). One of those lakes, Lake Möläkkä, was deeper (maximum depth 15 m, surface area 0.9 $\cdot 10^4$ m²). The temperature below at the depth of 3-5 m was 3-5°C in those lakes.

In three deeper lakes, the thermocline was at the depth of about 3-5 m, with a temperature of about 10°C. Those lakes were Lake Savijärvi (maximum depth 12 m, surface area 16.6 $\cdot 10^4$ m²), Lake Ylinen-Rautjärvi (maximum depth 12 m, surface area 37.6 $\cdot 10^4$ m²) and Lake Sorsajärvi (maximum depth 13 m, surface area 15.0 $\cdot 10^4$ m²). The temperature at the depth of about 7 m was about 5-7°C.

Surface temperature is strongly regulated by the weather, and it was rather similar for almost all of the lakes: 19.5-21°C. However, in one of the lakes, Lake Syrjänalunen (maximum depth 8 m, surface area 0.9 $\cdot 10^4$ m^2), the surface temperature was only 18°C. In that lake the water was mixed strongly, and the water temperature was still over 14°C at the depth of four meters, warmer than in any other of the lakes. In the rest of the shallow lakes the water temperature was about 5°C at that depth. Large temperature differences could be found between the lakes close to the surface: in the smaller lakes typically heat could not penetrate into the deeper layers. In the deeper lakes, at the depth of 2 m the temperature was even over 10°C warmer and, at the depth of 4 m about 5°C warmer than in the more shallow lakes at those depths. In the deeper lakes the temperature was about 6°C at the depth of 7 m, warmer than what was close to the bottom in the shallow lakes.

On 16-18 July 1985 observations were made at a total of 18 lakes. Their maximum depth was from 4 m to 14 m, with an average of 9.2 m and SD of 3.1 m (absolute value of SD is given for each SD). Surface area was from $0.4 \cdot 10^4$ m^2 to $45 \cdot 10^4$ m^2, with an average of 7.7 $\cdot 10^4$ m^2 and SD of $10.8 \cdot 10^4$ m^2. The temperature profiles were not very abrupt, thermocline was at the depth of from 2 m to 5 m, in deeper lakes it was deeper. However, there were two exceptional lakes. Lake Vähä-Valkjärvi (maximum depth 4 m, surface area 2.3 $\cdot 10^4$ m^2) was totally mixed and warmer than the others, about 22°C. Also in Lake Valkea-Musta (among the lakes modelled in this study) considerably more heat had settled down and the profile indicated much stronger mixing than in most of the lakes. The average profiles, including the variation of temperature along depth, are given in Fig. 1. There are not as many observations from deeper layers, as all lakes are not as deep as these two. That influences the average profile: below the depth of 5 m only the deep lakes affect it.

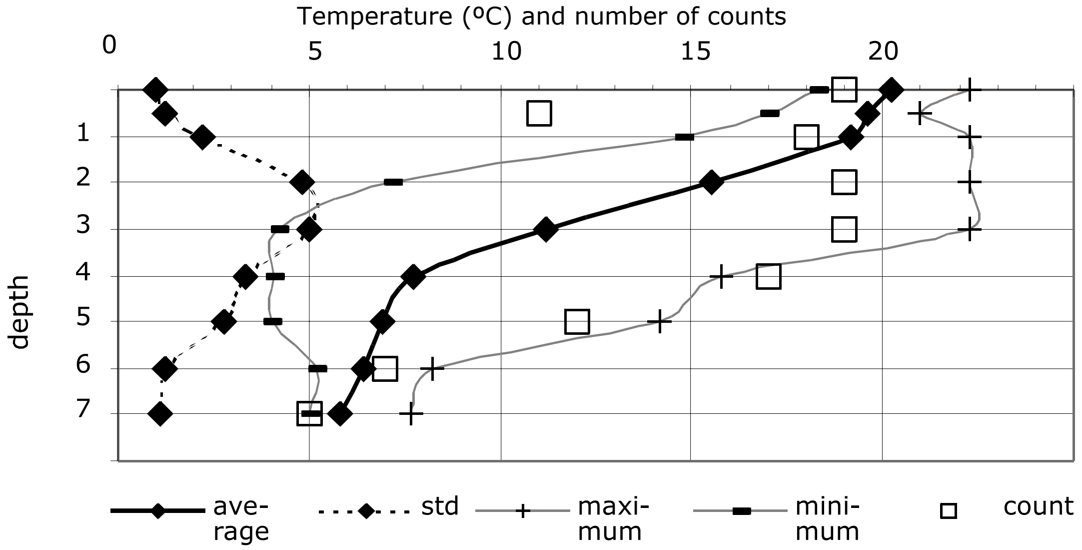

Figure 1. Average temperature profile for a set of small lakes close to Lake Pääjärvi determined according to measurements 16-18 July 1985.

Later in autumn, on 25-29 September 1985, measurements were made from the lakes in the same area. The lakes measured on the first day were among the warmest, but generally there were no large temperature differences. As this period was relatively short, it was representative of the situation at that time: some of the lakes had already experienced their overturn while others were still stratified. It was possible the lakes into two groups: almost all the larger lakes were mixed, but the smaller, more sheltered lakes were still stratified. The 11 mixed lakes had an average surface area of $12.6 \cdot 10^4$ m^2, with a maximum of $45 \cdot 10^4$ m^2 and a minimum of $0.3 \cdot 10^4$ m^2 (SD 15.6 $\cdot 10^4$ m^2). Their maximum depth was on the average 8.4 m, with a maximum of 13.0 m, and a minimum of 3.7 m (SD was 3.7 m). Sixteen lakes were still stratified. Their average surface area was much smaller, only $4.9 \cdot 10^4$ m^2 (maximum $14.9 \cdot 10^4$ m^2, minimum $0.4 \cdot 10^4$ m^2 and SD 5.4 $\cdot 10^4$ m^2). However, the maximum depths were rather the same as in the mixed lakes (average 9.4 m, maximum 15.0 m, minimum 4.0 m and SD 3.5 m). This shows that surface area is an important explanatory factor, but overturn had allready occurred insome very small lakes. The smallest of them, Lake Mekkojärvi (only 3 m deep, surface area 0.3 $\cdot 10^4$ m^2) had already cooled the most. The second smallest of the mixed lakes was Lake Alinen-Mustajärvi (surface area $0.7 \cdot 10^4$ m^2, depth 4 m). Lake Mekkojärvi was over 1°C colder than Lake Alinen-Mustajärvi, and it is unlikely that this was caused by cooling during the observations. Lake Vähä-Valkeajärvi (surface area 2.3 $\cdot 10^4$ m^2, maximum depth 4 m) was mixed and its temperature was 8.5°C. Two lakes with similar dimensions were still stratified: Lake Rieskalampi (surface area 2.3 $\cdot 10^4$ m^2, maximum depth 4 m) and Lake Kylökäs (surface area 2.3 $\cdot 10^4$ m^2, maximum depth 4 m). In them, surface temperatures were 8°C and 8.2°C, with a sharp drop of temperature deeper to 5.5-6°C. Although the lakes are so similar and close to each other, there were large temperature differences.

In both of the groups the average surface water temperature was 9.1°C. In the stratified lakes the temperature was on the average 8.7°C at the depth of 1 m and 8.1°C at the depth of 2 m. In the mixed lakes it was on the average only 0.1°C cooler at those depths. Even if the lake was mixed, the deeper lakes had cooled slower: the shallow lakes were about 1°C cooler than the deep lakes. Average temperature of the mixed lakes decreases therefore slowly downwards and even increases slightly at the depth of 5 –7 m. In the stratified lakes the average temperature changes vertically naturally much faster due to stratification, a thermocline (temperature about 6°C) can be found somewhere at the depth of 4-6 m. At the depth of 7 m temperature was on the average 4.8°C.

Weather changes during the period may have had some effect. If the three lakes measured in the first day (25 September) were excluded, the average temperature would decrease about 0.4°C for the first few meters. For some of the shallow lakes the overturn might have occured so recently that the actual observation timing and weather during the period was critical.

Strong absorption of light near surface maintains temperature stratification, but in autumn the amount of that energy decreases. Two sets of observations of secchi depths from the area (from year 1997) confirmed that the secchi depths in the area typically are close to 2 m. The bottom of some very shallow lakes could be seen, but the maximum secchi depth in summer was 5.5 m. Secchi depths also remained rather constant over the summer, especially in shallow lakes. In the lake where the deepest secchi depth was observed, the variations were also the largest. The temperature profiles measured together with the secchi depth observations showed that the thermocline was formed clearly below the secchi depth.

Virta et al. (2000) have used the same data to construct, calibrate and test a model of heating of hypolimnion. Some of the lakes had to be excluded because they were too shallow or the measurements were otherwise not deep enough to describe hypolimnic temperature. The model was based on dimensionless variables that were used to derive relations for the depth of the thermocline and temperature of hypolimnion. In the model the test function for the depth of the thermocline is calculated with

$$\frac{h_b}{H_L} = \frac{1}{\pi}\left\{\arctan\left[\log\left(pL^q H_L^r\right)\right] + \frac{\pi}{2}\right\}, \tag{20}$$

where h_b is the thermocline depth, H_L is the depth of the lake, and L is the length scale of the lake, the square root of the surface area of the lake (units m). p=9.521, q=0.691, and r=-3.06 are calibrated parameters. The model describes the ratio of the thermocline depth to the total depth with values between zero and one. The test function for the temperature of the hypolimnion is

$$\frac{T_b - T_0}{T_s - T_0} = \frac{1}{\pi}\left\{\arctan\left[\log\left(pL^q H_L^r\right)\right] + \frac{\pi}{2}\right\}, \tag{21}$$

where T_b is the temperature of hypolimnion (at the depth $(h_b+H_L)/2$), T_S is the temperature of surface and T_0 is 4, and the temperature of maximum density (units °C). $p= 8.47\cdot 10^{-11}$, q=5.15and r=-5.95 are calibrated parameters.

The variables are analyzed and given in relationships where the units can be cancelled. As equilibrium is thought to be reached, the formulation is suitable for seasonal development, and the values can best correspond to the values of August. The model cannot describe effects caused by different weather in separate years. It was calibrated with data from 1985 and tested with data from the following year. In Table 13 the values according to Eqs. (20) and (21) are calculated for the lakes modelled in Article VI and the values are compared to corresponding values with the model applications. These lakes are larger than the lakes that have been used for calibration and testing of the empirical model, but the results of the empirical model of the small lakes were compared to the PROBE model results. A constant value of 20.1°C was used as the surface temperature. A programme developed by Juhani Virta was used to calculate the thermocline depth from the modelled temperature profiles.

The corresponding temperature was also calculated and given in Table 13 together with the modelled surface temperature.

Table 13. Comparisons of thermocline depths and temperatures of hypolimnion. h_b is the thermocline depth (Eq. (20)) and T_b is the temperature in the hypolimnion Eq. (21) obtained with the empirical model. h_m is the thermocline depth obtained from profiles calculated with the PROBE model, T_{hm} is corresponding temperature, T_{bm} is the corresponding hypolimnetic temperature and T_{sm} is the modelled surface temperature (Article VI).

Lake	h_b Eq.(20)	T_b Eq.(21)	h_m -85	T_{hm} -85	T_{bm} -85	h_m -86	T_{hm} -86	T_{bm} -86	T_{sm} -85	T_{sm} -86
Pääjärvi	10.1	5.5	9.6	11.3	4.5	13.3	11.7	5.7	19.3	18.7
Valkea-Musta	4.3	5.7	4.1	16.5	5.4	5.0	16.0	7.1	21.3	20.7
Kallavesi (sub-basin)	8.6	9.2	7.6	15.0	6.1	7.2	15.9	6.4	17.9	17.5
Jääsjärvi	8.0	18.0	9.5	14.6	7.8	12.4	15.2	14.2	18.3	17.2
Vanaja	8.4	18.0	12.2	10.9	6.1	12.1	10.0	11.4	17.7	16.9
Näsijärvi	9.9	16.9	13.3	10.3	4.6	14.5	13.2	6.5	18.4	17.9

The values of the empirical model are close to those modelled with the PROBE for Lake Pääjärvi and Lake Valkea-Musta (the later is also among the lakes used for calibrating the empirical model). In Lake Kallavesi the thermocline is only about 1 m lower according to the empirical model in both of the years, but according to that model the hypolimnetic water is about 3°C warmer. The modelled sub-basin of Lake Kallavesi has a surface area of 41 km^2. The rest of the lakes have even larger surface areas and the empirical model gives substantially higher hypolimnetic temperatures than what is observed. The modelled thermoclines are formed about 4 m deeper than what the empirical model gives. Mixing in those larger lakes is strong, and it is even possible that in Lake Jääsjärvi and Lake Vanaja, overturn occurs during the summer. Lake Näsijärvi is the largest of the lakes. All of this supports the idea that mixing is much stronger in larger lakes and sheltering is much more important in small lakes. However, the correspondence between the methods for lakes with smaller surface area was rather good, even for the deep Lake Pääjärvi.

7.3. Lake Valkea-Musta

Some measurements and calculations concerning the heat balance of Lake Valkea-Musta have been presented by Blom (1981). Her work and data recorded by the Department of Geophysics at the University of Helsinki were used to construct the PROBE model application in Article VI. Calibration was based on data from 1979 and 1980. Temperature recordings for the summers 1982 and 1983 were used for verification (Fig. 2). Lake Valkea-Musta is smallest of the lakes modelled with the PROBE in this study. It is also among the small lakes used for the empirical model, but according to the observations its deeper layers were warmer than those of the other small lakes. It was possible to calculate the components of the heat balance with the PROBE application (Article VI) and to compare the results with those based on measurements by Blom (1981), presented in Table 14 and Table 15. They were used together with water temperature data for the calibration. For lakes with a small surface area, direct sunlight can be strongly reduced, even if the trees are highest obstacles in the landscape. Global radiation was measured at Lake Valkea-Musta in the summer of 1980, those data supported a reduction of 10%. Results (Fig. 2) show relatively good correspondence, also on the bottom of the water body.

Table 14. Monthly means of components of the heat balance for Lake Valkea-Musta in 1979 (given as values/measurements). *LE* is the flux of latent heat, *H* is the sensible heat, *R* is the radiation balance, and *Q* is the rate of the change of the heat balance (all in W/m^2). Values were calculated with data from Jyväskylä and calibrated with lake data (Article VI); measurements were from Blom (1981) (determined using measurements).

1979	June	July	August	September	October
LE	82/82	66/56	50/58	30/47	12/23
H	19/19	19/18	16/14	15/18	10/11
R	-121/-142	-92/-79	-56/-81	0/-23	28/10
Q	20/10	7/-1	-10/0	-45/-31	-50/-28

Lake Valkea-Musta was not included in Article VII because of insufficient long-term ice data. According to the model ice break-up occurred on 13 May 1979 and 2 May 1980, compared to the observed dates of 3 May 1979 and 28 April 1980. In the model the ice break-up is very much determined by air temperature, but controlled by radiation balance. If global radiation were not reduced the ice cover would remain intact five days longer in 1979 and seven days longer in 1980. This conclusion further supports the reduction. In spring, shores absorb heat especially when snow cover has disappeared, which can intensify the increase in air temperature. The effect is more important for lakes with a small surface area, due to the vicinity of the shores. That effect is not included in the model, and its absence can explain why ice break-up is observed earlier than modelled.

Table 15. Monthly means of components of the heat balance for Lake Valkea-Musta in 1980 (given as values/measurements). *LE* is the flux of latent heat, *H* is the sensible heat, *R* is the radiation balance, and *Q* is the rate of the change of the heat balance (all in W/m^2). Values were calculated with data from Jyväskylä and calibrated with lake data (Article VI); measurements were from Blom (1981) (determined using measurements).

1980	June	July	August	September	October
LE	83/77	63/56	58/55	20/25	13/16
H	17/16	15/15	20/20	10/11	12/5
R	-133/-133	-102/-134	-43/-79	0/-29	29/7
Q	33/27	24/20	-35/-24	-30/-19	-54/-25

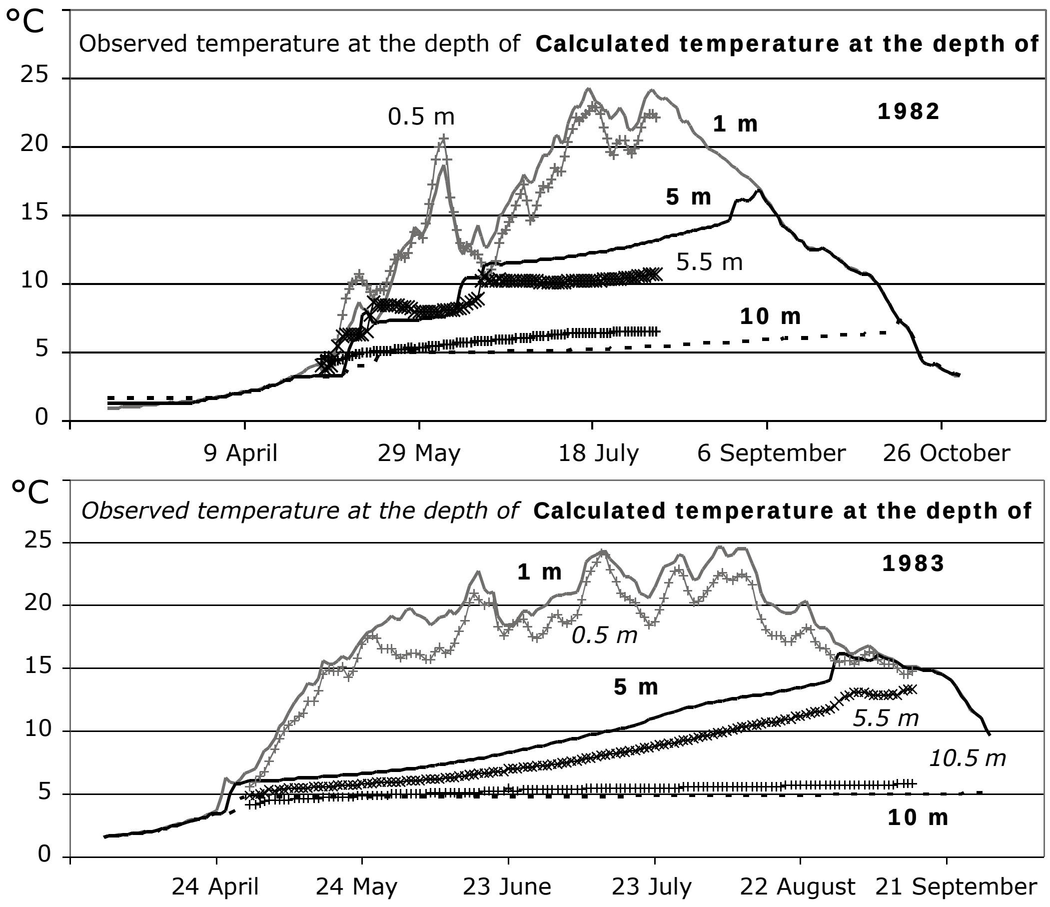

Figure 2. Temperature in Lake Valkea-Musta during summers 1982-83. Values are calculated with the PROBE model (article VI), the available observations for the period are shown.

7.4. Lake Vanaja

Calibration was based on continuous temperature profile data from the main basin recorded in the summer of 1983. The lake remained stratified all that summer, but the temperature difference between epilimnion and hypolimnion was usually only about 2°C (6-10°C during warmer periods). Water close to the bottom warmed throughout whole summer, and reached about 17°C at the end. Usually, according to model calculations, the top layers become warmer, but at the bottom water temperature remains relatively unchanged. If mixing is increased this distinction can even be intensified. When the deep-mixing routine was used, the water was excessively mixed and was almost isothermal all the time. The deep-mixing routine clearly does not suit a shallow lake. The modelled temperature structure was strongly influenced by input (air temperature, wind speed and extinction coefficient), but it was possible to modify them in such a way that the main features were rather well described. The heat intake was still excessively step-wise and the lowest layers were heated only later in summer.

It was possible to use a number of temperature profile soundings for certain dates in two summers (1975 and 1976) for verification (Fig. 3). Those soundings were taken close to the central part of the main basin; in the calibration year 1983 temperature was recorded little further from the center of the basin. The soundings on 4 September and 17 September 1975 were also made in a slightly different place, but according to them the lake was already mixed. Generally the temperature range was calculated rather successfully, but the same cannot be said of all the individual profiles. The lake was stratified, but not strongly. In the beginning of summer 1975 a short stratified period was followed by overturn.

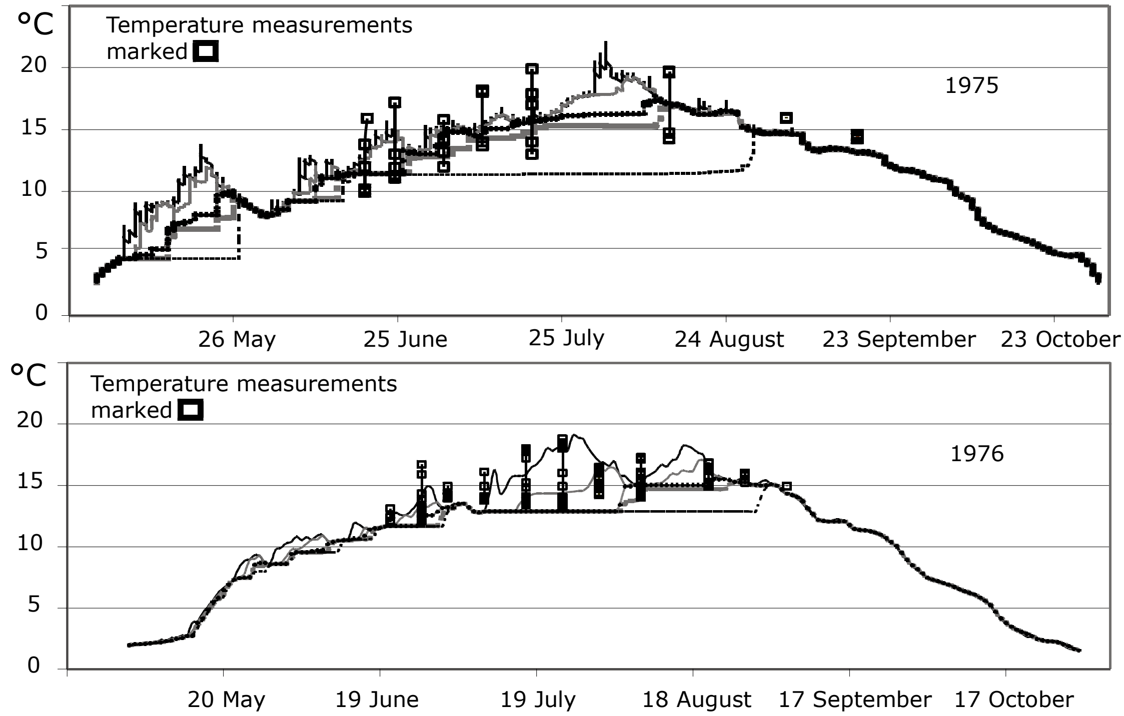

Figure 3. Temperature in Lake Vanaja during summer 1975-76. Temperature values were calculated with the PROBE model (article VI), the time series are from up to down: the surface and the depths of 5, 10, 15 and 20 m. The available measurements from the corresponding depths are from 19 and 24 June, 3, 10 and 19 July, 13 August, 4 and 19 September 1975 and 21 and 27 June, 2, 9, 17, 24 and 31 July, 8, 21 and 28 August and 5 September 1976.

7.5. Lake Jääsjärvi

Temperature chain recordings beginning in 20 June 1979 and lasting throughout freezing were used for calibration. Attention was focused on the cooling period. Temperature chain recordings from the years 1980-82 were used for verification (Fig. 4). It was difficult to obtain the correct temperature for the middle layers of the lake, even when the calculated temperatures at the surface and close to the bottom were rather close to the observed temperature. Calculations for the summer of 1980 showed that the epilimnion was too abrupt. This was also the case in 1981, but then the calculated water temperature was closer to measurements, partly because the surface layers were mixed all the way down to 10 m at the end of June. However, the beginning of the stratification and the corresponding depth agree rather well with the measurements. For the summer 1982 the modelled and observed temperatures were in better agreement at all three depths shown. It seems that overturn occurred in June. This indicates that it is difficult to find suitable mixing for the lake, possibly due to the complex shape and consequently, the dynamics of the lake. Local variations are possible, but it is not possible to deduce them from the data from distant synoptical stations. Such variations can also occur from year to year. The data used for the model application were from a distance (on the meso scale), namely from the city of Jyväskylä. The calibration was not only made according to summer water profile temperatures, but especially by adjusting the cooling of the water in autumn. However, in all the verification years the calculations showed that the water cooled a little faster than was actually measured.

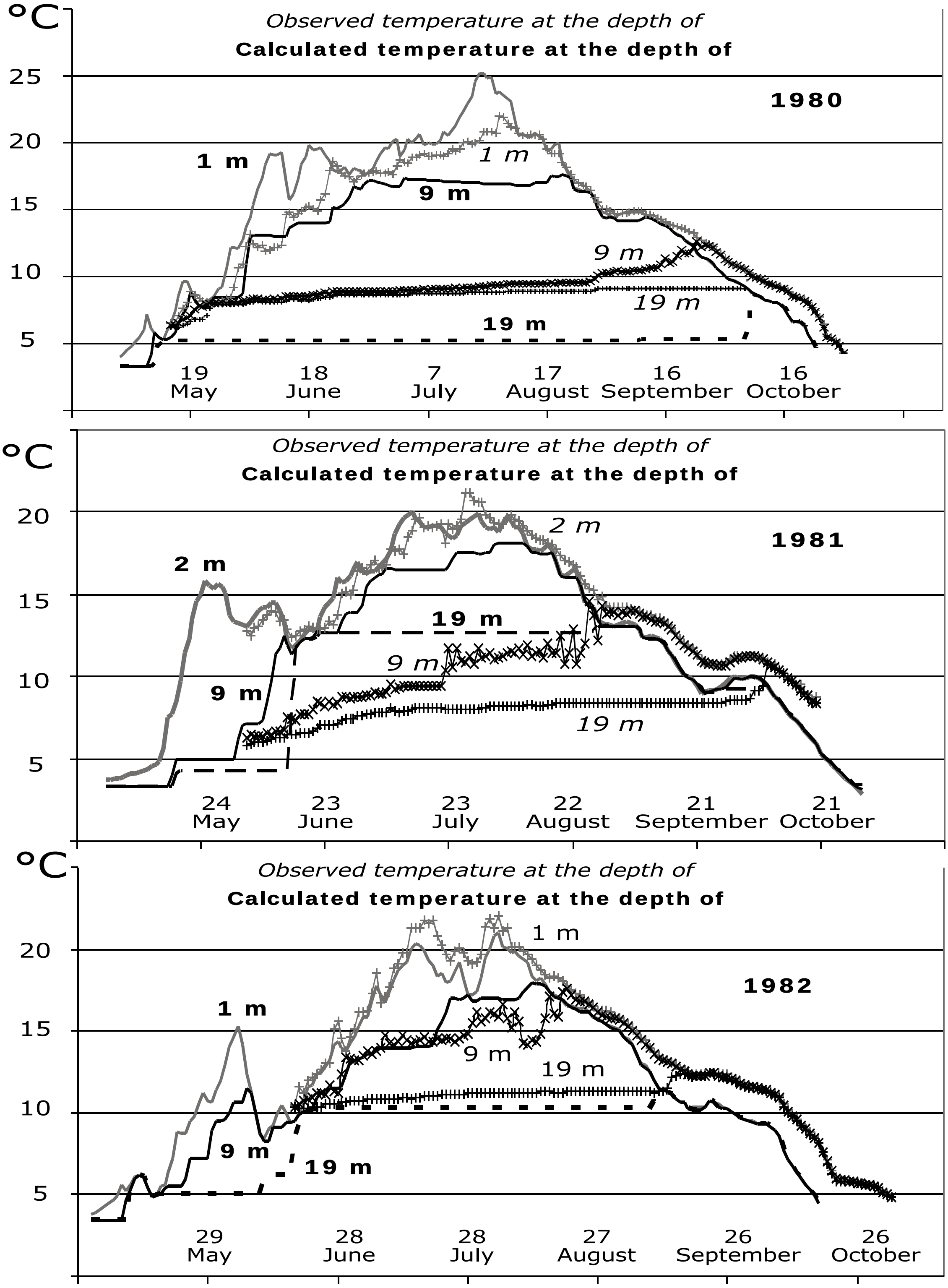

Figure 4. Temperature in Lake Jääsjärvi during summer 1980-82. Values were calculated with the PROBE model (paper VI), and the available observations for the period are shown.

Lake Jääsjärvi was also modelled with the HBV model, using the model of the watershed of Mäntyharju, including Lake Jääsjärvi. This HBV model calibration and the model simulations were made with Ari Koistinen, by the research tead directed by of Bertel Vehviläinen in SYKE. The normal data and the calibration of the HBV model were used, based on several stations in the vicinity. The obtained coefficients for Eq. (4) were k=0.093 and l=2.4. The calculated values begin on 1 August 1961, and the period 1980-1989 was used for calibration. From late June to September 1979, which was the period used for the PROBE model calibration, the PROBE results gave 1-2°C higher temperature than the measured temperature with high peaks: diurnal variations. Those peaks cannot be reached by the HBV model, because they were smoothed by the daily time step. The measured surface temperatures were also slightly smoothed after night. They are observed at the depth of about 0.01 m, close to the shore as is usually the case with the surface temperature recordings. The HBV model gave slightly lower temperature values than those measured before September. Later in autumn both of the models gave results that were rather close to the measured values.

The HBV model results were generally rather similar for the years 1980-1982, and the measured values were smoother and slightly lower. Summer 1980 was warmer, and the surface water temperature was higher than in the other years. The differences between the observed and the calculated values were slightly larger, but again the HBV model gave lower and the PROBE model higher values than the measured values. In May 1981 PROBE results show a warmer period, ending with mixing of surface water. This peak was not seen in measurements from the shore. For these dates the HBV model showed a steep round peak, and its calculated temperature was then higher than the measured temperature. The PROBE model gave a peak temperature that was 6°C higher; the results were similar after cooling and mixing. At the beginning of summer 1982 there was also a warmer period when the surface temperature dropped by 8.6°C for 12 days at the end of June and overturn almost occurred. Later that summer measurements show that water in the deeper parts was 2-5°C higher in 1982 than in 1981. The corresponding surface temperature peak was reflected also in shore observations and in the HBV model results. In 1981 ice break-up was relatively late: it was observed at 19 May. The standard PROBE model gave 17 May (Article VI), and the modified model (Article VII) gave 14 May for that year. With the PROBE model water temperature under the ice was heated several degrees before ice broke up and heating thereafter was intense. According to the results of the HBV model, water temperature remains constant at 0°C until ice is broken. This occurred on 15 May 1981. At that time the difference in water temperatures between the models was 5-10°C.

For comparison of the model results the monthly averages of the surface temperatures were calculated for summer months for the period 1990-1997 using the same application as in Article VI. Table 16 and Table 17 describe the statistics of the monthly surface temperature. Octobers were included, although in some years ice froze at the end of the month. That did not occur often, and the water is already rather cold at the end of the month, so the effect is not large. The lake was frozen on the average on 17 November, both both of the models giving the following day (1962-96, available observations). Values were calculated also for Mays, but larger errors in water temperature can occur at the time of ice break-up. Simojoki (1940) had observed that ice break-up on Lake Jääsjärvi took an average of eight days. Ice break-up occurs on the average on 4 May according to data available for 34 years for the period 1961-1997. With the application in Article VII, ice break-up took place on 5 May for the period 1950-1997 and 2 May for the period 1917-1949. The average date was also 4 May for the period used for the model comparison: springs 1962-9 (SD of 8 days, absolute value given for each SD). According to HBV model, ice break-up occurred on 22 April (SD of 12 days). The PROBE model gave the average date 7 May (SD of 7 days).

The statistics show that the average surface temperature was rather close to that obtained with the HBV model, and it was used to calibrate the model. The statistics are difficult to interpret straightforwardly: the PROBE model gave higher surface temperature measurements than the measured values, although the standard deviation was smaller on the average. The range of the observed values was smaller, although the values from the PROBE model were smoothed morning values. Before autumn, the temperature values given by the HBV model were too low, but in autumn higher. With the PROBE the surface temperature was on the average higher and especially the peaks are higher: the model was able to describe rapid heating more effectively.

Difficulties were observed in determining the date of freezing with the HBV model. Freezing is set to occur when the calculated water temperature is zero, but air temperature often rises after that, sometimes several times if the winter is mild. A similar problem has also been encountered with the PROBE model: after freezing ice breaks up and freezes again, even several times. Usually the final freezing date has been used to determine the freezing date. For the PROBE model, using the available observations for the period 1961-1996, the difference between observed and calculated dates was 1 (SD 12), with maximum of 52 and minimum of -13 days. If using the HBV model, the first date of ice in autumn is determined as the date of freezing, the values were 1 (SD 11), 32 and -31. If the last date when ice appears is used as the freezing date, the values would be 22 days (SD 17), maximum 59 and minimum -2 days. Winter 1972 was especially problematic, as it was rather warm and windy and the models gave several warmer periods. The lake was actually frozen already on the 20 November. That was the date for which the HBV model calculated the first ice, but the last freezing date was 29 December. With the PROBE model, the date was as late as 11 January, but the first ice was formed also as early as with the HBV model. These problems are extremely important for more exceptional years and attention should be given to such years and the possibilities of modelling them. The HBV model found the ice dates if they are defined as the first and last dates with cold water, but it is not clear what the periods with warmer water temperature between those dates mean. The HBV model would also have difficulties describing periods with milder winters, with partial ice cover and successive periods with and without ice cover, because it is not possible to treat actual warmer periods.

No such difficulties were encountered when modelling spring conditions, and ice break-up was practically final when it occurred. When the HBV model was used, the difference between the observed and the calculated dates as 12 (SD 11), maximum 48 and minimum -15 days for 34 springs. The corresponding values with the PROBE model were -3 (SD 8), 5 and -39 days.

Table 16. Surface temperature for Lake Jääsjärvi A. Values (°C) were calculated for the period 1990-1997, showing average values for the months over the whole period as observed, together with standard deviation and the count, i.e. the number of (daily) values used in the calculation. Observations were made in the morning. PROBE model (based on Article VI) values were the morning values; HBV model values were calculated daily. Temperature was observed at the depth of about 0.01-0.02 m, PROBE values describe the very surface of the profile and the HBV model values give only the surface temperature. (Absolute value of SD is given.)

	Av. Obs.	SD Obs.	Count Obs.	Av. PROBE	SD PROBE	Count PROBE	Av. HBV	SD HBV	Count HBV
May	9.7	3.1	212	9.2	3.1	248	9.0	3.1	248
June	15.8	2.7	240	16.4	2.5	240	15.1	2.5	240
July	18.1	2.4	246	19.1	2.2	248	17.7	1.5	248
August	17.3	2.7	241	19.1	2.4	248	17.6	1.7	248
September	11.0	2.8	228	12.5	2.6	240	11.9	2.7	240
October	5.0	2.6	242	5.5	2.7	248	6.2	2.4	248

Table 17. Surface temperature for Lake Jääsjärvi B. Values (°C) were calculated for the period 1990-1997, showing maximum, minimum and range of the temperature for the months over the whole period as observed, together with standard deviation and the count, the number of daily values used in the calculation. Observations were made in the morning. PROBE model (based on Article VI) values were morning values, HBV model values were calculated daily. Temperature was usually observed at about the depth of 0.01-0.02 m, PROBE values describe the very surface of the profile and the HBV model values give only the surface temperature. (Absolute value of SD is given.)

	Max. Obs.	Min. Obs.	Range Obs.	Max. PROBE	Min. PROBE	Range PROBE	Max. HBV	Min. HBV	Range HBV
May	18.0	2.8	15.2	18.4	3.6	14.8	16.3	0.9	15.4
June	23.6	11.0	12.6	22.4	11.0	6.0	19.8	9.9	9.9
July	24.3	13.7	10.6	24.7	15.3	5.6	21.8	14.7	7.1
August	24.3	10.9	13.4	25.8	14.3	6.7	22.1	12.6	9.5
September	18.0	4.1	13.9	19.6	7.6	7.1	18.2	5.2	13.0
October	10.0	0.0	10.0	11.3	0.1	11.2	11.0	0.1	10.9

7.6. Lake Näsijärvi

The application for Lake Näsijärvi in Article VI was developed using temperature profile observations from the years 1970-2000. Unfortunately, because the observations were probably made at different deep locations, the deviations are large. The long-term average profile for July was calculated. It was rather stable and did not change markedly with slightly different averaging sub-periods. The calculated average temperature profile for at least ten years was used in calibration. The goodness of fit for the period 1970-1997 was analyzed: calculated temperature values were selected from the times and depths the observations were available. The results are shown in Table 18. On the average the computed surface temperature was close to the measured values, but at the depth of two meters the calculated temperature was higher, then lower at five and ten meters, then higher again at deeper temperatures. This also shows that it was hard to reach the shape of the profile. In addition to the deep layers, the top layers were also difficult to model, even if the surface temperature is affected by its strong interaction with the atmosphere. The relative difference between calculated and observed temperature values at various depths also varies, but is small on the average. Even the same absolute difference would give a greater relative difference, when the relation is calculated by dividing with a smaller value; the temperature is lower at deeper layers.For two springs, some larger deviations, e.g. for surface temperature, were close to ice break-up at the beginning of May. The temperature time series at different depths are shown in Fig. 5.

Table 18. **Temperature differences between observed and calculated temperatures at different depths for Lake Näsijärvi.** Number of counts was 455 for 15 m depth and 456 for the other depths.

Depth	**0**	**2**	**5**	**10**	**15**	**20**	**24**
Average temperature difference	0.3	2.9	-0.6	-1.3	0.6	1.8	2.0
Average of relative temperature difference	0.0	0.1	-0.1	-0.1	0.0	0.2	0.2
SD of relative difference (absolute value)	0.2	0.3	0.2	0.2	0.2	0.3	0.3

7.7. Lake Kallavesi

Water temperature profiles from the years 1981, 1984 and 1985 were used for calibration of the application in Article VI. The observations were made two to five times per month. The lake remained stratified, but typically the temperature in the hypolimnion increased the whole summer. Only the use of the deep-mixing routine gave this feature. The shape of the basin supports the use of this routine because it is rather deep compared to the surface area.

For further analyzis of the successfulness of the application more temperature profile data were used. It was possible to use profiles for 32 summers from the years 1964-1997 for verifications. The results are shown in Table 19. The calculated surface temperature agreed with the observed values. Deeper, the average difference becomes larger, but the average relative difference stays smaller than 0.2. Standard deviations of the relative difference remain practically the same along the profile. The temperature time series for the depths are shown in Fig. 6.

Table 19. Temperature differences between observed and calculated temperatures at different depths for Lake Kallavesi. Number of counts was 487 at each depth.

Depth	**0**	**5**	**10**	**15**	**20**	**30**	**40**
Average temperature difference	0.0	0.0	1.2	1.7	1.7	1.8	1.6
Average of relative temperature difference	0.0	0.0	0.1	0.1	0.1	0.2	0.2
SD of relative difference (absolute value)	0.3	0.3	0.3	0.3	0.3	0.3	0.2

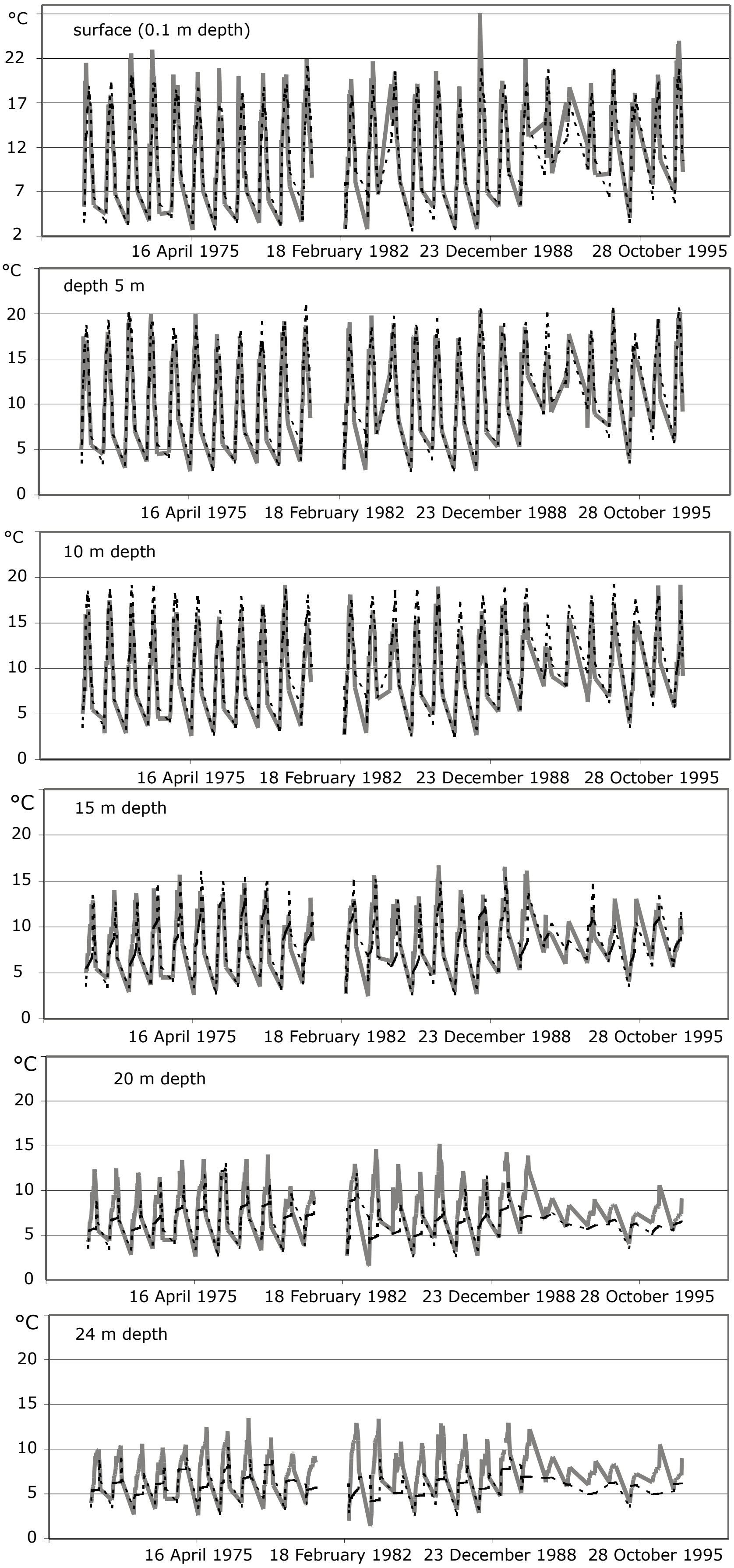

Figure 5. Temperature in Lake Näsijärvi during1970-1997 (summer period). Calculated values, drawn with dashed line, are obtained with the data from Jyväskylä (Article VI). Observed temperatures are drawn with solid line. Each depth is shown at the corner of the pictures.

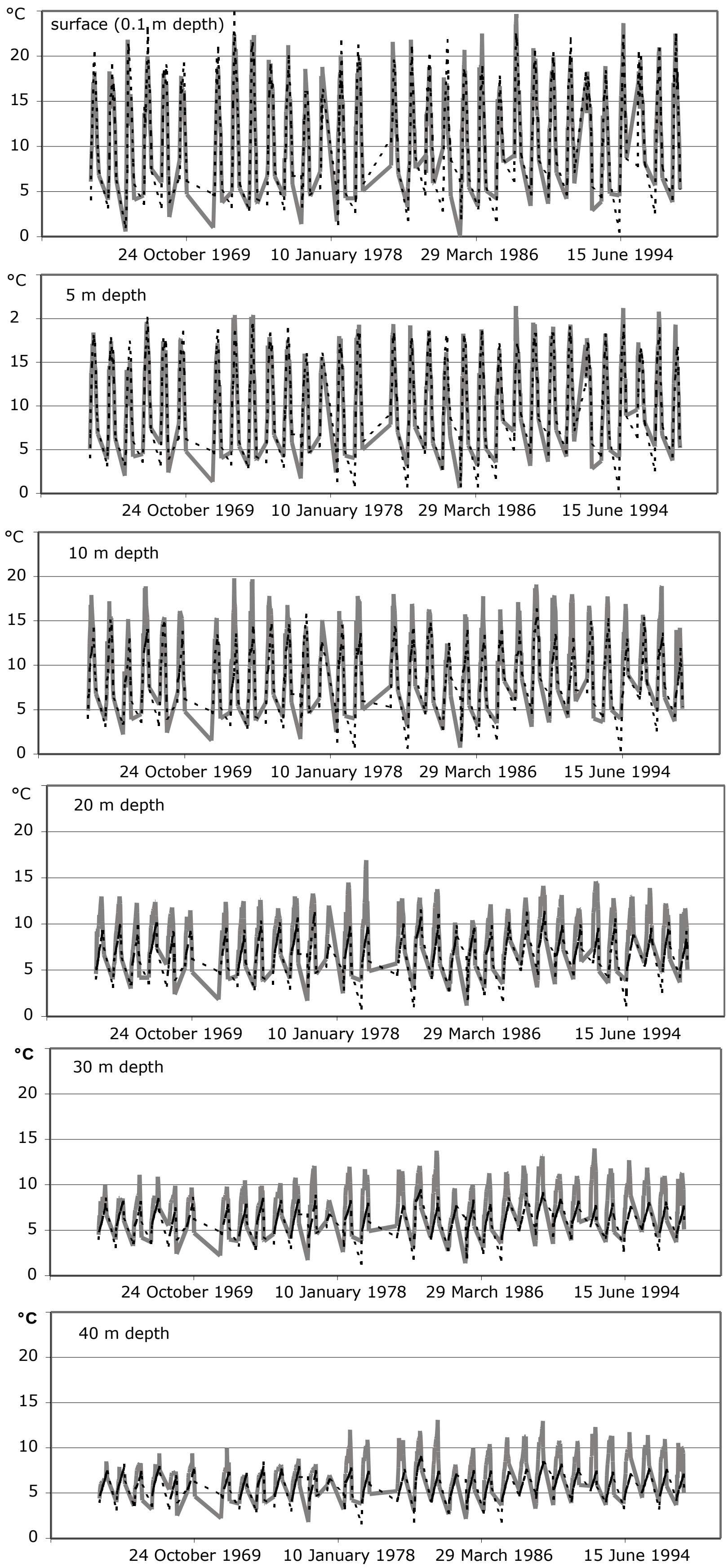

Figure 6. Temperature in Lake Kallavesi during 1970-1997 (summer period). Calculated values, drawn with dashed line, are obtained with data from Jyväskylä (paper VI). Observed temperatures are drawn with solid line. Each depth is shown at the corner of the pictures.

7.8. Lake Constance

Meteorological data series were available from the years 1979-95, including air temperature, relative humidity, wind speed and direction. Global radiation was also measured. These data were used by Ollinger (1999) with a lake *kε*-model. His model was similar to the PROBE model, but in his version temperature was coupled with a biological extinction model, which used also measured radiation data directly as input. These meteorological data represent Upper Lake Constance best; most of the data were from that area and were adjusted to its dynamics. The wind field was also compared to measurements from the main basin. Wind has strong directional effects, and these have also been identified in lake seiches, which have also been related to water exchange between the basins. The model by Ollinger has been used in studies of the impacts of interannual variability in hydrodynamic conditions on plankton development by Gaedge et al. (1998). The influence of weather conditions have been discussed by Ollinger and Bäuerle (1998).

A PROBE model application was applied to Lake Constance, and the ice model was used to model the rare freezing. Local conditions at the lake were different than for the other lakes modelled, including global radiation. The location also has an effect on the dynamics of the lakes through the Coriolis force, which influences the seiches in the lake. Latitude is often used when calculating global radiation, but proper adjustent is highly important. The PROBE lake application model was mainly used in some basic sensitivity studies. The first version used cloudiness (and latitude) for solving global radiation input, as was also done in most of the earlier model applications. Measurements of the absorption of light in the water (Ollinger 1999) were used to estimate an average value for the extinction coefficient, 0.5 m^{-1}, corresponding to an euphotic layer of about 3.5 m. The model was found to be very sensitive to the value, and changing the value to 0.05 m^{-1} was able to change, among other things, the tested spring situation, dramatically resulting in much smaller temperature change along the profile. It was possible that the thermocline was formed at about the same depth, but temperatures of epilimnion and hypolimnion were changed by several degrees. The temperature difference was large, particularly at the surface layers, and this had a strong influence for ice formation. On this basis the effect of optical properties could be regarded as most important aspect to be considered in connection with climate change evaluations.

It was possible to collect additional meteorological data and tests were performed to study the connection to the climate within a PROBE application (Elo 2000). The winter 1962-63, which was the only winter of the 20th century when the lake froze was especially interesting. Therefore the succesful result for the period is to model ice cover for that year but not for the rest of the winters. The data from the period 1979-92 used by Ollinger (1999) were used first. The calculation of the density of water was not modified, although the density differences in the deep parts of the lake during winter at relatively low temperature might be relatively important. The meteorological data before the year 1979 had to be treated differently, but nearby comparison data were available.

Measured data were used for calibration of the level of global radiation, and as a test the freezing for the period 1961-1964 was studied, included the rare freezing. With the obtained corrections the results for the baseline period (1975-1995) were improved considerably, but some unrealistic freezing remained. Twice there was ice cover for five days and once for two days, but longer periods were also obtained: for 1982 13 days and for 1984 11 days. The monthly means of the data did not give any clear explanation (the weather was cold during those periods, but there were some other cold periods when ice was not modelled). Apparently the dynamics of the lake prevented freezing, and this was not adequately described by the model. Occationally there is some ice at the shores of the lake. The results did not change essentially when values 0.5 and 0.7 for extinction coefficient were used, as only a few additional daily episodes of ice cover were produced with the latter value. Monthly mean values of the dynamic eddy viscosity were still typically unusually high (Fig. 7). Variations are large, in the monthly mean values the absolute values obtained can also be regarded as large, especially in deep parts of the lake. This may be an indication that for more reliable results density should be described with formulas better suited to take small differences into account.

For the year 1963 ice cover was calculated rather well: formation on 6 February (observed 5 February) and ice break up on 13 March. 14 March the main basin was still partly frozen (Wagner 1964). In 1962 ice almost formed, in 1964 there was ice for one day. This result was obtained with extinction coefficient β=0.5. With β=0.7 the ice cover period in 1963 was from 23 January to 19 March. Ice was formed for two days also in 1962 and for one day in 1964. If the water was very clear (β=0.05), ice was formed only for the period 7-11 March 1963. However the extinction coefficient used here can have an important effect on ice cover formation; a constant value was used for these simulations.

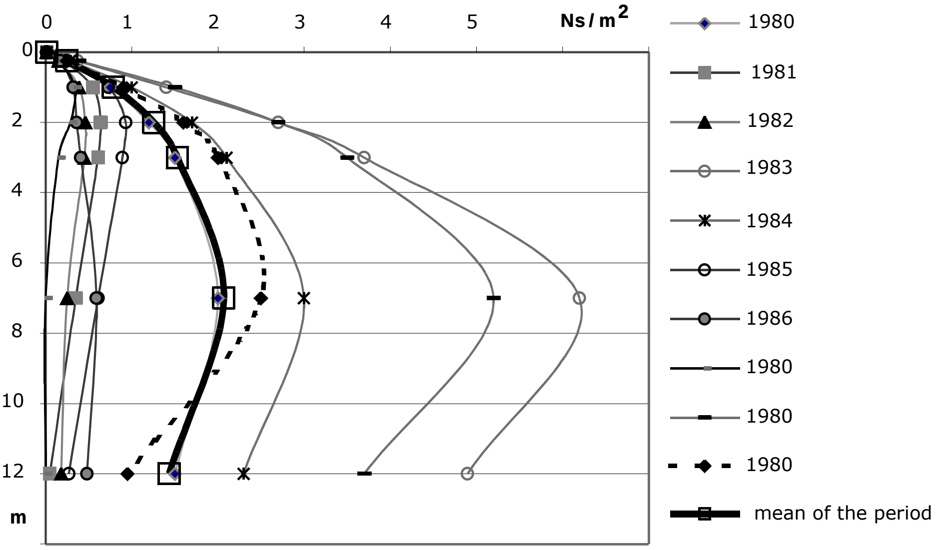

Figure 7. Monthly means of turbulent dynamic eddy viscosity in January. Values were calculated with a PROBE application for Lake Constance (Elo 2000).

The computed water surface temperature was compared with measured values using data from a station close to the southernmost part of the main basin. Average values for July months during the period 1980-1989 were calculated. With β=0.5 their mean value was 23.3°C (SD 2.1°C, absolute value of SD is given for earch SD.), which was 2.6°C (SD 0.5°C) higher than the measured value. With β=0.7 the calculated mean value was 23.4°C (SD 2.2°C). The differences are systematic, except in some years, as seen in Fig. 8.

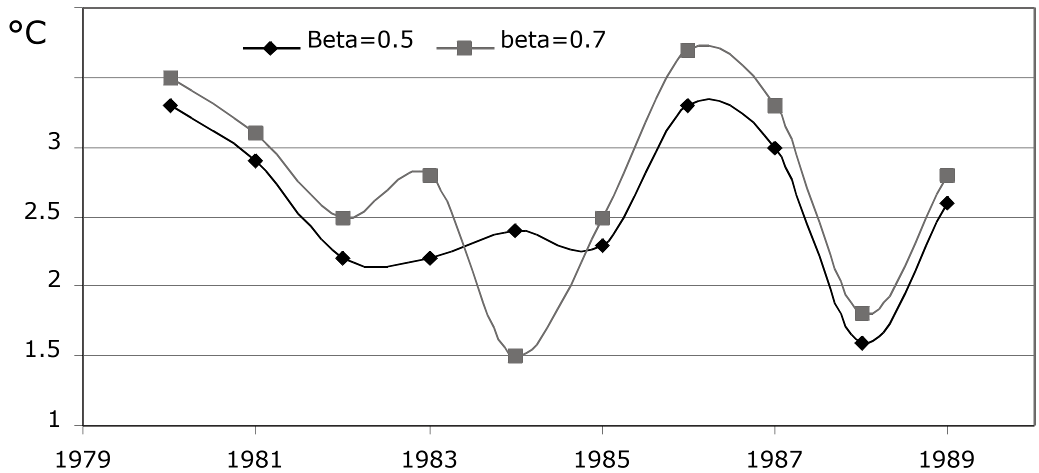

Figure 8. Surface temperature difference in July for Lake Constance. Measured value is subtracted from the corresponding values obtained with the PROBE model (Elo 2000).

The possibilities of a one-dimensional model are limited by its suitability for the application and the assumptions made. In a case of a rather complicated system like that of Lake Constance, many factors may be of great importance. The data from 1979 onwards correspond better to the Upper Lake Constance, but Ollinger (1999) adjusted the model and compared the results to measurements over the main basin. The water exchanges between the upper and main basins as well as the seiches were analyzed. Additional mixing may be caused by mechanical turbulence at a certain depth, e.g. river throughflow. Water-level and flow data were also available for use in estimating the importance of river throughflow. The water-level was rather low at the beginning of 1963, and the outflow was relatively small. This might have had some importance for dynamical effects, but no systematic study was made. Regulation and flow peaks as well as other changes may also have effects. It is also possible that flow peaks can change the water content due to all the advected material in the lake.

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